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Introduction

Apparently because I am among a minority of scientists (Springer 2014, Sims 2011, Hansen 2008, Hansen 2016, and EFN 2018) willing to say that today’s politically correct (non-nuclear) renewable energy sources couldn’t support even the near future’s (2050 AD) human population without severe environmental consequences, I was asked to contribute a chapter to an upcoming soil science book describing how a "nuclear renaissance" could address Africa’s especially imposing future issues (Siemer 2020). That morphed into one of QUORA’s longest-ever winded “answers” which, in turn, inspired this effort (QUORA 2018).

I’m a 74 year old, retired Idaho National Laboratory (INL) “Consulting Scientist” (first, analytical research chemist, then chemical engineer, and finally, radwaste materials scientist) who had spent much the last ten years of his career trying to “whistleblow” about how INL’s previous mission (serving as DOE’s “lead lab” in radwaste management) had been (and is still being) managed\(^1\). This book will first explain why nuclear power should and could become the world’s primary energy/power source and then identify the reasons that it’s become so difficult to develop a “nuclear" technological fix for the future’s energy

\(^1\) Before I went to work for DOE, I had spent my first four, post-PhD, years as an Assistant Professor of Chemistry at Marquette University. I’d quit because it had become apparent by then that what I was good at doing – teaching, student recruitment, and experimentation – wasn’t nearly as important in academia as is bringing in “outside money” -- something for which I had (and still have) neither interest nor talent. I’d also recently been informed by a contractor that I had hired to install aluminum trim on my house that my salary was under that which he was paying his “help”. Consequently, when someone made me a “too good to refuse” offer at a spectroscopy conference that I had taken my senior graduate students to(both got their PhD’s before I left), I decided to give the “real world” a try.
conundrums. It is neither another review of the history of nuclear power nor a summary of other peoples’ work and opinions. For the most part, those efforts/opinions will be summarized and “open access” references given so that readers can read them themselves (which I encourage). It is largely autobiographical and seeks to encourage its readers to do the same thing that’s guided me throughout my scientific career: “think for yourself and do it with numbers”. The biggest difference between this and the books written by others sharing my enthusiasm for nuclear power (e.g., Rhodes 1993, Rhodes 2018, Cravens 2007, Till 2011, Bryce 2010, Bryce 2013, Beckers 2016, Beckers 2017, Crane 2010, Erickson 2019 & Goldstein 2019), is I am a technical nerd “ex insider” more aware of the nuclear industry’s foibles.

Anyway, after I’d retired, I decided to take advantage of the “openness” provided by the internet (not DOE) to determine for myself whether or not we actually needed a “nuclear renaissance”, the development/promotion of which had become INL’s “new mission”. After pondering the current suite of alternatives had convinced me that the world does indeed need such a renaissance, I then looked into why we didn’t just go ahead and implement one capable of addressing the Future’s energy-issues; i.e. one based upon breeder-type reactors. The

2 The reason for basing decisions/opinions upon “numbers” is that many ideas/claims that initially appear to be perfectly reasonable prove to be unreasonable when examined quantitatively. Most “advertising” – one of today’s most lucrative service industries – relies upon most peoples’ reluctance to do simple math.

3 A breeder reactor generates at least as much fissile material as it consumes. It can do this because their neutron economy is high enough (they don’t waste neutrons) to create (“breed”) more fissile (233U, 235U, or 239Pu) than they “burn” (fission) via neutron capture by fertile materials (238U or 232Th) also within the reactor. Breeders were initially considered absolutely necessary because they make far more efficient use of natural uranium (NU) than do light water reactors, but interest plummeted after the 1960s when more uranium was discovered and a
root cause of that failure turned out to be the same cultural “symptoms” responsible for turning the treatment of DOE Hanford’s/INL’s “high level wastes” (HLW), opening a HLW waste repository, & building a MOX-type\textsuperscript{4} reactor fuel factory, into multibillion dollar boondoggles. My own experiences within DOE’s laboratories along with what’s happened since I retired leads me to suspect that most of its nuclear engineers and scientists quite understandably are not “really serious" about much other than continuing to quietly study their little non-controversial piece of "all of the above"\textsuperscript{5} until they can retire too.

There is a tremendous need for more and better “energy services” to fuel economic development and provide energy security throughout the entire world, not just within its currently rich societies. By circa 2100 AD (and preferably sooner) we must build "clean" (greenhouse gas (GHG) free) energy systems capable of powering the homes, factories, transportation systems, and cities of a world that’s even more environmentally compromised with ~50% more people to support. The supply speed and scale of such change is unprecedented. Those needs cannot be satisfied for some people at the expense of others – the rich can’t just keep getting richer while everyone else’s lives become more precarious.

\textsuperscript{4} MOX = ”mixed oxides” of plutonium and uranium.

\textsuperscript{5} During the USA’s last two presidential administrations, “all of the above” has included gas, oil, wind, solar (two flavors), geothermal, “big hydro”, low head hydro, wood/palm oil/switchgrass/corn/rapeseed/soy-based biofuels, “beautiful clean coal”, and conventional nuclear power.
Today’s economic development models are largely based upon continued consumption of fossil fuels and therefore pose serious threats to the environment. Local side effects include pollution, land degradation, forest fires, and water scarcity. Globally, climate change creates increased risk of extreme weather events such as floods and drought, as well as changes to our ecosystem like sea level rise, forest loss and ocean acidification. Climate change is already impacting millions of people, particularly the world’s most vulnerable populations, which is why mankind really does need to embark upon an all-out effort – a “nuclear green new deal“ - to combat both climate change and the economic consequences of this century’s almost-inevitable “peak oil”, “peak gas”, and “peak coal”.

While this book will demonstrate why a properly implemented nuclear renaissance could address the future’s energy issues more effectively than could any combination of the currently politically correct renewable energy sources, it won’t dwell exclusively upon such things – it’ll be pro nuke, not anti-anything except the cultural pathologies that have rendered significant progress in this arena almost impossible in the USA.

My goals include:

- Show readers how to “think for themselves” about technical issues with lots of worked-out examples and homework problems.
- Try to convince my ex colleagues at the USA’s national laboratories that it is absolutely necessary “get serious” about implementing a genuinely sustainable nuclear renaissance
- Remind them that there's a pretty good chance of succeeding if they screw up enough resolve to pull their heads up out of their leaderships’ drawers.
• Explain why the US federal government’s nuclear engineering (NE) experts have not done “the right thing” with respect to developing practical solutions to the world’s nuclear energy conundrum.

To support “controversial” opinions I will be presenting numerous examples of both my and others’ experiences with the US Department of Energy’s (DOE’s) management of nuclear energy-related projects.

Since the African continent’s people are apt to be the most severely impacted by the future’s demographic, environmental, resource limitation, and economic challenges, most of my nuclear renaissance’s “killer apps” will invoke solutions to Africa’s issues. Like those detailed in David Mackay’s book “Sustainable Energy: Without the Hot Air” (Mackay 2009), my examples will be numeric (quantitative) and based upon reasonable assumptions and readily obtained (GOOGLEable) data, not sweeping generalizations, over simplifications, or the sorts of wishful thinking often reflected in disquisitions invoking nuclear powered utopias. Doing so will undoubtedly offend some of my pro-nuclear colleagues because some of the reactor concepts that they are currently championing are much less “equal” than others (Orwell 1945).

I will also be putting the results of numeric examples into proper perspective: “naked” numbers – especially, very large or small ones presented with “strange” units\(^6\) – often mislead even scientists and engineers.

\(^6\) For example, discipline-specific units like “barrel of oil equivalent” (BOE) are often rendered even less intuitive with unmentioned assumptions having to do with how that energy is to manifest itself (as process heat? electricity?). Little “technical details” like that are important.
This book’s scenario is that by 2100 AD, a “sustainable nuclear renaissance” – not an “all of the above” mix of today’s politically correct renewable energy sources with or without more-of-the-same nuclear reactors– will be addressing the root causes of most of mankind’s misery throughout the ages. Among the wonderful things that such a renaissance would render possible, food production would become genuinely sustainable because cheap/clean electrical power would simultaneously address the world’s water woes and enable the mining, grinding, shipping, and distribution of sufficient powdered basalt over farmland to affect Mother Nature’s too slow, notoriously unreliable and sometimes catastrophic (volcanic) approach to both soil-building and atmospheric CO₂ removal. It would also enable the mining, grinding, shipping, and distribution of sufficient ultramafic rock-based sand to sea shores and reefs to protect them from rising sea levels and reverse oceanic acidification (Schuiling & Krijgsman, 2006).

The world’s nuclear scientists, especially the USA’s, must screw up enough courage to discard their blinders and concentrate upon developing practical solutions to real problems. Addressing the future's energy-related issues will require lots of big “sustainable” reactors powering a world-wide industrial "new deal" like that envisioned by Alvin Weinberg almost a lifetime ago, not just more of the USA’s recent “all of the above” energy research muddling. If thinking that way means that I’m a “trouble maker or “unpatriotic”, that’s something I certainly can live with.

Notes:

- I’ve decided to not include a GLOSSARY because GOOGLEING has rendered such things superfluous.
- Regardless of why you’ve decided to read this book, pay attention to its footnotes & work out your own answers to its homework
problems (who knows? My answers might be wrong) – learning how to do “technical stuff” requires effort.

- If you want to contact me, “correct” me, or suggest additions to a future edition of this book, feel free to send me a note.
Chapter 1.  Africa’s especially special issues

Unlike most first world nations, the majority of Africa’s 54 countries continue to exhibit alarmingly high rates of both population growth and poverty (ESA 2015). Approximately 380 million of its ~1.2 billion people are extremely poor – often hungry – and ten of the world’s most underdeveloped (Trump 2018) countries – Mozambique, Guinea, Burundi, Burkina Faso, Eritrea, Sierra Leone, Chad, Central African Republic, Democratic Republic of Congo, and Niger – are located therein. Furthermore, although considered exceptionally underdeveloped, none of them are among the twenty countries recognized to possess the world’s lowest living costs (Cheap 2018) meaning that Africa’s poor people are considerably poorer in fact than are those in more technologically advanced but poor by OECD standards nations like Romania. Most of Africa’s people are plagued by a lack of basic infrastructure due to dysfunctional and, often, self-serving governance further complicated by long-festering civil/tribal/religious conflicts and therefore face bleak futures. Much of Africa is also apt to be particularly hard-hit by climate change - the Sahara desert is expanding bigger. The fact that most of its countries are ill equipped to deal with any sort of natural disaster, possess economies comprised primarily of subsistence farming on progressively poorer-quality land, and have grossly underfunded public health, physical infrastructure, and

7 “Life has become more brutal and brutish”, Wole Soyinka (84 year-old Nigerian playwright & philosopher). CGTN interview, 16Feb2019.

8 Much of Spain, Portugal and the southwestern US is becoming desert-like and each year’s heat waves are killing more people everywhere.
education services constitute only some of the factors considered in compiling quality-of-life rankings. Most of the United Nation’s measures of Human Development (UNDP 2018) also consider the fairness of income/wealth distribution for which Africa’s countries are also especially low-ranking (GINI 2018). Cambridge’s Sir Partha Dasgupta, recipient of almost every award that economists can bestow, has pointed out that most of the recent GNP increases of 2\textsuperscript{nd}/3\textsuperscript{rd} world countries have come at the expense of their average citizens’ personal assets (Dasgupta 2003).

Africa’s (and the World’s) still burgeoning population growth exacerbates all of its problems. As of 2015, the UN’s mid-range population growth projection is that Africa will have \(~4.5\) billion inhabitants by 2100 AD – about three times that similarly anticipated for the world’s currently most populous nation, China. The populations of 28 African countries are predicted to more than double between 2015 and 2050 and, by 2100, those of Angola, Burundi, Democratic Republic of Congo, Malawi, Mali, Niger, Somalia, Uganda, United Republic of Tanzania and Zambia are to increase at least five-fold.

Frankly, I consider such projections unrealistic. First, the western world’s increasing “populism” (extreme polarization often bordering upon fascism) driven primarily by rapidly increasing class, power, and wealth disparities but usually blamed upon foreigners. Second, the armed-to-the teeth “leader of the western world”’s nervousness about the fact that its dominance of the world’s economic system is rapidly diminishing could cause it to become overly aggressive. Third, more refugees than ever are being forced to flee their homes due to human
violence (war, terrorism, and persecution) and rapid climate change but often have no place to go. Fourth and finally, the fact that the world will soon be facing the consequences of peak oil, peak coal, and peak gas. Both “human nature” and most of human history suggests that those factors may ignite another “world war” apt to kill far more people than did the 20th century’s and thereby curb (or reverse) the 21st century’s population growth.

Unless a new, worldwide, “Fair Deal” somehow comes to pass, the relative demographic weight of the world’s developed countries will drop shifting economic power to developing nations. The already-developed countries’ labor forces will age and decline constraining their economic growth and raise the demand for cheap non-documentated immigrant workers which will likely further increase the frequency of killings, burnings, and bombings driven by jingoistic populism. Most of the world’s population growth will be concentrated in the poorest, youngest, and most heavily faith-based (mostly Muslim) countries many of which will continue to be unable to provide adequate education, capital, and employment opportunities for their young people.

9 Over human history, climate changes—usually drought—have probably driven more people to abandon their homes than anything else. Today’s world is far more crowded than were those inhabited by Greenland’s Norse settlers, the Ottoman & Khmer empires, and Mexico’s Mayan & India’s Indus Valley civilizations which means that today’s refugees are finding it more difficult to settle anywhere else.

10 The Fair Deal was an ambitious set of proposals continuing Roosevelt’s New Deal liberalism revealed by U.S. President Harry S. Truman in his 1949 State of the Union address. Its most important proposals were aid to education, universal health insurance, the Fair Employment Practices Commission, and repeal of the Taft-Hartley (anti-union) Act. However, because a Conservative Coalition controlled Congress, they were all debated and then voted down.
Finally, most of the world’s population will live in cities, with the largest such heavily urbanized areas in the poorest countries, where adequate policing, sanitation, health care, and even clean water are likely to be available only to their richest inhabitants. Such urbanization is apt to be profoundly destabilizing. People moving to cities within developing countries during the rest of this century are apt to have far lower per capita incomes than did those of most of today’s industrial countries when they did so. The United States, did not reach 65 percent urbanization until 1950, when its per capita income was nearly $118,000 in 2019 dollars. By contrast, countries like Nigeria, Pakistan, and the Philippines now approaching similar levels of urbanization, have per capita incomes of $2,300–$5,200. Countries with younger populations are especially prone to civil unrest and less able to create or sustain democratic institutions. The more heavily urbanized they become, the more they are apt to experience grinding poverty and anarchic violence. In good times, a thriving economy might keep urban residents employed and governments flush with sufficient resources to meet their needs. More often however, people living in sprawling, impoverished cities are victimized by crime lords, gangs, and petty rebellions. Thus, the rapid urbanization of the developing world is apt to bring in more exaggerated form, the same problems that urbanization brought to nineteenth-century Europe: cyclical employment, inadequate policing, and limited sanitation and education which spawned wide-spread labor strife, periodic violence, and sometimes, even revolutions. International terrorism originates in fast-urbanizing developing countries. Within poor sprawling megacities like Mogadishu and Damascus, neighborhood gangs armed with internet-enabled social networking offer excellent opportunities for the recruitment, maintenance, and hiding of terrorist networks (Goldstone 2010).
When life is cheap, worthwhile jobs unavailable, and the future looks even worse, young people often to go to war.

US Pentagon studies (CNA 2014) concluded that the root cause of the majority of such deaths will be disease and starvation engendered by the disintegration of technology-dependent societies dependent upon increasingly limited/degraded resources (land, food, fuel, high grade ores, etc.). In his book, "Small is Beautiful: A Study of Economics as if People Mattered", Ernst Schumacher (Schumacher 1973) observed that today’s technological civilization is unsustainable because the finite resources enabling it are treated as inventory (income) rather than capital. The sustainability of today’s economic systems therefore requires continued growth of both population11 and total wealth (GDP), both of which are impossible in a finite world.

Second, if our world’s future leaders were to decide to implement the changes needed to address the technical issues otherwise likely to lead to war, doing so would result in much lessened fertility (CATO 2013). Figure 1 depicts the effect that increasing people’s prosperity12 has upon

11 The Earth now supports about three times as many people as it did when I was born and five times more than when my grandfather was. Most of that growth is due to the fact that our energy-enabled civilization’s technological advances have decreased child mortality (not raised birth rates) and rendered it possible to feed far more people. I suspect that if this book’s utopian scenario were to come to pass, human population will gradually drop back to a level (2-3 billion?) consistent with both much more comfortable lives for individuals and more room for other living creatures.

12 Norway’s performance at the last Winter Olympics exemplifies how the “UN’s Inequality adjusted human development index” reflects a county’s citizens’ “quality of life”. Half way through that gathering, Norway, with only 1.6% of the USA’s population, had won almost twice (37/21) as many medals. Why? It’s not because its people are “richer” than are the USA’s: a bit of GOOGLING reveals that Norway’s after-tax GDP/capita income level is almost identical to the USA’s - $45,348 vs $45,648. The real reason is that because Norway’s people govern
their reproductive choices (replacement fertility ~2.1) - if the future were to become both much richer and fairer than it is now, today’s unsustainable population growth would quickly end.

Figure 1: Prosperity vs human reproductive choices (WIKIPEDIA data)

themselves in a way that benefits them rather than powerful special interests including overly-entrenched duopolistic political parties – their tax dollars support them, not serve special interests. Its policies have generated a much more equitable distribution of wealth/GDP top-to-bottom than the USA has (it’s got very few poor and almost no homeless people); its medical service providers can’t force anyone into bankruptcy due to injury or illness; its public schools are much better than the USA’s; its federal government doesn’t profit by increasing its college students’ debt burdens; and its employers must grant its citizens far more paid leave than the USA’s are entitled to (25 days/year Norway vs zero USA). It’s also unlikely that Norway’s government routinely forces its “essential” employees to work without pay (slavery?) while its politicians bicker with each other. Consequently, Norway’s people feel much more secure, freeing them to do whatever they wish, including fun things like skiing that only “lucky” Americans can afford. This argument explains the relative per capita athletic performance of other northern European nations’ and Canada’s Olympic teams to the USA’s. The USA’s electorate also doesn’t seem to care that their top political leadership’s credo seems to be: "For whosoever hath, to him shall be given, and he shall have more abundance: but whosoever hath not, from him shall be taken away even that he hath" (Matthew, 13:12).
Consequently our leadership’s objective should become encouraging the development of a genuinely sustainable and much more egalitarian world in which every individual regardless of where they live or who they are does indeed matter. Until they acknowledge the above-related facts, embrace appropriate goals, and begin to act accordingly, we'll all just continue to spin our wheels while blaming “the other guys”.

What are those goals?

Since food represents any living creature’s most fundamental need and its source for humanity is farm land, I’ll begin by describing what’s been happening along those lines in the world’s currently most undeveloped continent, Africa. A recent Brookings Institute report (McArthur 2013), points out that, “no matter how effectively other conditions are remedied, per capita food production in Africa will continue to decrease unless soil fertility depletion is effectively addressed.” It goes on to say that a second major problem with the oft-assumed African “land abundance” hypothesis is its inconsistency with convincing evidence that its soils are being simultaneously depleted and eroded by current agricultural practices including a decline in fallowing. While some African leaders along with the management of “land grabbing” (?) international agribusiness concerns seem to feel that Africa still has plenty of yet-undeveloped arable land, many of Africa’s poorest people (mostly subsistence farmers) can’t afford to let any of theirs lie fallow and thereby recover: some families live on 0.36 ha (0.9 US acre) farms yielding under 1 t of grain/ha (t=tonne=10^3 kg=10^6 grams):

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13 “The test of our progress is not whether we add more to the abundance of those who have much; it is whether we provide enough for those who have too little.” — Franklin D. Roosevelt
ha=hectare=10^{4} m^2=2.59 US acre) while the first-world’s farmers routinely produce 3 to 12 t/ha of whatever cash crop they chose to plant on several order of magnitude larger farms\textsuperscript{14}.

The key differences between the agricultural practices of developed nations and most of Africa’s include:

• Developed nations heavily fertilize their croplands – most of Africa’s farmers can’t afford artificial fertilizers and often have to burn any manures or crop residues they can gather to cook their food

• Developed nations’ farmers can afford to irrigate their croplands – most of Africa’s can’t. That issue is compounded by the fact that much of Africa’s nominally arable land doesn’t get enough rain to reliably support anything other than skeletal cow or goat grazing.

• Most developed-nation farms are both large and productive enough to enable their owners to buy/utilize specialized machinery which renders their labor far less exhausting and much more rewarding. The world’s poorest farmers still work themselves to death with primitive tools

• Developed nation farmers can afford to use hybrid seeds that increase yields and resist hazards, such as drought, fungus, or microbes.

• Developed nation farmers can afford to use advanced herbicides and insecticides

• Developed nation farmers have storage facilities and efficient food distribution networks

\textsuperscript{14} Including its little “hobby farms”, the average size of a farm in the USA’s Corn Belt is about 350 acres and such land is now worth about $9000/acre
Chapter 2. Why everything boils down to energy inputs

It is evident that the fortunes of the world’s human population, for better or for worse, are inextricably interrelated with the use that is made of energy resources.

M. King Hubbert

Those differences simply reflect the relative amounts of raw/primary energy supporting the lifestyles of rich vs. poor people, which still boils down to their relative per capita fossil fuel consumption. Since I’m going to be supporting most of my contentions with the results of ball park calculations, let’s start this off with a table containing many of the numbers/terms that will be used throughout complete with their units (for brevity’s sake I’ll be leaving the units out of most of this book’s example calculations)

Table 1: “Special” numbers, constants, etc. along with their units

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.15E+7</td>
<td>number of seconds per year [3600<em>24</em>365]</td>
</tr>
<tr>
<td>24</td>
<td>= 24 hrs/day (8760 hrs/year)</td>
</tr>
<tr>
<td>365</td>
<td>= 365 days/year =365 days/a</td>
</tr>
<tr>
<td>3.2E-11</td>
<td>(energy) = # of Joules generated by the fission of a single actinide atom (=’s 200 million electron volts (MeV))</td>
</tr>
<tr>
<td>6.023E+23</td>
<td>= 6.023E+23 = number of atoms, molecules, etc., per gram mole of anything</td>
</tr>
<tr>
<td>1.6E-19</td>
<td>= number of electron volts per Joule (the combustion of a single carbon atom generates 4.1 electron volts)</td>
</tr>
<tr>
<td>Watt</td>
<td>(power) = W = energy/second = Joule/s = J/second = J/s = 0.00134 mechanical horsepower</td>
</tr>
<tr>
<td>kWh</td>
<td>(energy) kilowatt hour = 1 J/s<em>3600 s/hr</em>1000 = 3.6E+6 Joules (most common unit for electrical energy)</td>
</tr>
</tbody>
</table>
GWyear = Giga W yr = 1E+9*3600*24*365 = 3.15E+16 J
(energy) (x) may be thermal (x=t) or electrical, x=e (GWe)
Calorie (energy) = 4.19 J = 0.001 kilocalorie =0.001 kcal
(energy)
Acre (area) = 43560 ft² = 4049 m² = 0.4049 ha = 0.0015625 mile²
BTU = British thermal unit =1055 J (energy required to heat
(energy) one pound (454 g of water) 1 degree F or 5/9 degree C)
Quad (energy) = one quadrillion BTU = 1.055E+18 J
BOE (energy) = barrel of oil equivalent=6.1E+9 J (assumes a
(energy) 42 US gallon barrel, 10 kcal/g, and 0.916 g/cc oil)
nX = 10⁻⁹*X = nano X
kX = 10⁻³*X = kilo X
MX = 10⁻⁶*X = mega X
GX = 10⁻⁹*X = Giga X
TX = 10⁻¹²*X = Terra X
EX = 10⁻¹⁸*X = Exa X

On-farm agricultural energy consumption in rich (developed) countries entails the burning of diesel oil, gasoline, and/or LP gas in engines plus use of electricity made by burning another fossil fuel, usually coal. Consumption is considerably higher in high-GDP countries (around 20.4 GJ/ha) than it is in low-GDP countries (around 11.1 GJ/ha) and far greater than on Africa’s subsistence farms (Giampietro 2002). For example, most of the energy input to a subsistence farm consists of human labor which, throughout an 8 hour work day, averages about 75 watts per person (Human Power 2018). If 100% of such useful (in this case, mechanical) energy [2.16E+6 J/day = 75J/s*8hr*3600 s/hr] is devoted to cultivating a 0.9 acre (0.36 ha) plot throughout a 6 month growing season, the area-normalized “energy services” devoted to it is 1.08 GJ/ha/a [2.16E+6 J/a*365days*6/12/2.47 acre/ha/1E+9], which is
about ten percent of the raw/primary food energy required to keep each person so-occupied alive throughout the entire year [2500 kcal/day *365 days/a]. Energy-wise that’s not very efficient – state of the art farm machinery generates about one third of a joule’s worth of useful energy from a joule’s worth of fuel heat energy and doesn’t consume anything when not running.

According to a “Food and Agriculture Organization of the United Nations” (FAO) report (Sims 2011), the raw/primary energy consumed by the world’s “food sector” amounts to ~95 EJ (exa (10^{18}) Joules) per year – approximately 20 percent of current total global raw/primary energy consumption (~570 EJ/a =18 TW) – and generates over 20 percent of anthropogenic greenhouse gas emissions. Land use changes, particularly those linked to the deforestation brought about by the expansion of agricultural lands to raise food crops and biofuels (IPCC 2007) constitutes another ~15 percent of anthropogenic GHG emissions. Only about 5% of that energy, ~6 EJ, directly supports on-farm activities such as cultivating and harvesting crops, pumping water, housing livestock, heating protected crops, drying and, short term storage. The rest/majority of the agricultural sector’s energy demand is devoted to transport, fertilizer and pesticide production, food processing, packaging, storage, and distribution.

All of the world’s developed countries adopted Dr. Borlaug’s fossil-fueled “Green Revolution” which enabled ~90% of today’s ~7.5 billion people to consume as much food – both basic necessities along with some luxury items – as they want (Borlaug 2019). Approximately one half of the world’s current population would quickly starve if that hadn’t happened. However, the fossil fuels enabling both it and the 20th century’s industrial and information revolutions generated huge environmental impacts including the greenhouse gas (GHG) emissions
responsible for global warming/climate change. From 1870 to the present, fossil fuel burning dumped about 580 Gt (Giga tonnes) C into the atmosphere in the form of ~2100 Gt of CO$_2$. That gas partitioned between the atmosphere, oceans and land, warming all of them and thereby causing increasingly severe and frequent weather events including “Super El Niños” (Hong 2016), ocean acidification, drought and biofuel production-driven food cost escalation, air pollution, deforestation, potable/irrigation water shortages, sea-shoreline erosion/flooding, and relentless cost of living increases in the world’s poorer regions. Those effects constitute threat multipliers that aggravate human stressors – poverty, environmental degradation, hunger, political instability, and social tensions – and thereby engender mass migrations plus a great deal of terrorist activity and other forms of violence.

James Hansen probably possesses the world’s most “educated” opinions about the causes, effects, and consequences of global warming. They’ve been summarized as follows (Hansen 2018):

1. Climate has always changed, but humans are now the main driver for change

a. Rising atmospheric CO$_2$ levels, primarily a result of fossil fuel emissions, have become the predominant cause of continuing climate change

b. Climate change is driven by cumulative CO$_2$ emissions. The U.S. has contributed a disproportionately large share of cumulative global emissions.
2. Current levels of atmospheric greenhouse gases (GHGs), mainly CO$_2$, cause Earth to be out of energy balance. This imbalance is driving climate change.

a. Earth’s energy imbalance is now measured and large. As long as Earth remains out of energy balance, the planet will continue to get hotter.

b. If GHG amounts continue to rise unabated, the energy imbalance will drive global warming to levels with climate impacts beyond the pale (see 3)

3. If high fossil fuel emissions continue unabated, consequences will be predominantly negative for humanity, especially for young people.

a. Sea level: Continued high fossil fuel emissions will eventually make coastal cities dysfunctional, with incalculable consequences.

b. Species exterminations: Shifting of climate zones, with other stresses, may commit many species to extinction, leaving a more desolate planet.

c. Regional climate: subtropics and tropics will become dangerously hot, if high emissions continue. Emigration chaos may threaten global governance.

4. Required actions to avoid dangerous climate change are guided by Earth’s climate history and by the need to restore Earth’s energy balance

a. Science can specify initial targets, sufficient to define policy needs
b. Emission reductions must begin promptly, or climate will be pushed beyond a point at which changes proceed out of human control

5. The U.S. government, via both actions and inactions, is behaving with flagrant disregard of rights and well-being of the public, especially young people

a. Action: authorizing, permitting, subsidizing massive fossil fuel extraction

b. Inaction: absence of any coherent, effective program to reduce them

During the ~150 years since we began to power ourselves with fossil fuels, two world wars and numerous smaller ones have been fought over access to natural resources – primarily “lebensraum” (land) and fossil energy resources, usually petroleum – some of which resulted in the Christian-country “winners” creating new countries in the oil rich Islamic Persian Gulf, which, of course, eventually engendered more conflict.

Securing those resources has proven to be expensive to those war’s winners. A Princeton University report concluded that simply keeping the US Navy’s fifth fleet within the Persian gulf from 1976 to 2006 had cost its taxpayers ~$6.8 trillion 2008 dollars and would probably cost them another $0.5 trillion during 2007 (Stern 2010) which figures didn’t include the costs of actual conflicts. Since that fleet remains on station, the total cost of “maintaining presence” therein has now probably reached about $12 trillion. A 2013 Kennedy School of Government report (Foreignpolicy 2013) concluded that the total cost of the USA’s
most recent wars in the Middle East and Northern Africa would probably be $4-6 trillion and had accounted for roughly 20 percent of its increase in national debt between 2001 and 2012 (modern wars are fought with borrowed money).

Concerted international effort to address fossil fuel’s environmental impacts began with the UN’s 1997 Kyoto Protocol to which many, mostly small and not particularly impactful, countries signed up. While the billions of dollars spent on climate science research since then have generated thousands of papers/reports and paid for hundreds of other conferences both large and small, neither that science nor the policy changes of many countries favoring/subsidizing politically correct renewable energy have had much effect upon mankind’s GHG emissions. As this is being written (December 2018) representatives from 195 countries have again gathered (in Katowice, Poland) for this year’s United Nations Climate Change Conference, COP 24 (COP = “Conference Of the Parties”). This meeting is focused upon producing rules to flesh out the “details” of the 2015 Paris Climate Accord (COP 21), the landmark agreement signed by all of its attendees except Nicaragua and Syria, to battle climate change and, hopefully, limit global warming to 1.5 degree Celsius, one-half degree under the 2°C limit set earlier at COP 15 (the Copenhagen conference). Since 2015, the International Panel on Climate Change’s (IPCC’s) leadership has been trying to breathe new life into that accord amid backsliding from several key nations, most notably the United States, over commitments made when they signed it. To date, the IPCC’s efforts have not really accomplished much because key “parties” refuse to agree upon a mechanism ensuring that they honor their commitments with respect to either GHG emissions or contributions to a $100 billion/a climate mitigation fund.
The latest version of the British Petroleum company’s annual Statistical Review of World Energy (BP 2018) contains not only information from the preceding year, but also historic data on consumption and production of all forms of energy during the last several decades. Its principal conclusion is that humanity is not reaching the goals established by the Paris Agreement (see Fig 2). In 2017, Mankind took a step backwards with respect to the timid advances made during the two preceding years: the use of fossil fuels had grown, increasing CO₂ emissions by ~1.6%. That trend continues – anthropogenic CO₂ emissions rose another 2.7% in 2018 (Jackson et al, 2018). Worse, most climate models indicate that by 2100 AD, even if the emission “commitments” made by COP 21-24’s attendees were to be honored, they would likely cause global warming of between 2.7 and 3.2 degrees Celsius, well above the 1.5–2 degree threshold that many climate modeling experts consider a tipping point beyond which Nature’s positive (?) feedback mechanisms will render catastrophic impact inevitable (Hansen 2008, Hansen 2016).

One such mechanism would be sudden release of the vast amounts of methane trapped along continual shelves in the form of “methane hydrate” (aka methane clathrate). Such methane is produced when microorganisms or chemical processes break down organic matter that settles to the seafloor, including dead fish, krill, miscellaneous plankton, and bacteria. A methane hydrate “ice” accumulation can form only when temperatures are low and pressures are high. If part of such a deposit is exposed to warmer temperatures or a drop in pressure, it can suddenly turn to gas thereby tremendously expanding its volume which stirs up everything surrounding it. That in turn increases convective heat transfer to any nearby more deeply buried surrounding ice destabilizing it as well. This constitutes a positive feedback “chain reaction” which may cause sudden release of the entire formation’s methane accumulation. That release in turn further heats the atmosphere some of which heat will
further warm coastal waters containing other methane ice deposits. This mechanism is probably what set off the Paleocene–Eocene Thermal Maximum (PETM), 55 million years ago that spiked global temperatures upwards by 5-8 °C (far more than that required to melt both Greenland and Antarctica’s ice caps & thereby worldwide sea levels by several hundred meters).

“We are waking up the methane dragon. And that’s a dragon that we really want to keep in the box”. Samantha Joye, oceanographer and microbiologist.

Furthermore, a recent paper (Yvon-Durocher. 2014) indicates that for each degree that the Earth's temperature rises, the amount of methane entering its atmosphere from microorganisms dwelling in lake sediment and freshwater wetlands -- currently the primary sources of that gas -- will increase several fold. As temperatures rise, the relative increase of methane emissions will outpace that of carbon dioxide from those sources. There’s also vast amounts of methane trapped within the Arctic’s currently frozen muskeg, which, along with that emitted by more southern wetlands and rice fields, is apt to cause runaway global warming.
The most important thing that we must do is to quickly replace today’s fossil fuel-based energy system with something that is both “clean” (no GHG gas emissions) and sufficiently reliable (not intermittent) to power a bigger, more interconnected, more prosperous, cleaner, fairer and happier world than is the one we’re living in today.

"To prevent the worst effects of climate change, we need to reach near-zero emissions on all the things that drive it—agriculture, electricity, heating, cooling, industry, and transport."
manufacturing, transportation, and buildings—by investing in innovation across all sectors while deploying low cost renewables,"

Nuclear energy is one of these critical technologies. It's ideal for dealing with climate change, because it is the only carbon-free, scalable energy source that's available 24 hours a day." Bill Gates

2.1 How much clean sustainable energy will our descendants need?

The exceptionally “rich” lifestyle\(^{17}\) of the USA’s ~320 million people is nominally supported by about 99.5 EJ (98 quads) of raw/primary energy per annum, which figure has remained roughly constant for over two decades (LLNL 2018). It’s “nominal” because its consumer-driven economy consumes energy and other resources from areas outside of and greater than the USA’s which isn’t counted in such compilations. “Ecological footprint analysis” (Wackernagel 1996) provides us with a more realistic measure of the USA’s resource

Table 2: US Greenhouse gas emissions including those originating from products/services made abroad

<table>
<thead>
<tr>
<th>Service</th>
<th>Percent total GHGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure</td>
<td>1</td>
</tr>
<tr>
<td>Appliances &amp; devices</td>
<td>7</td>
</tr>
<tr>
<td>Non local passenger transport</td>
<td>9</td>
</tr>
</tbody>
</table>

\(^{17}\)“rich” in terms of material things – most of the USA’s people own more stuff”, drive further in bigger cars and live in much larger houses than do average Europeans.
Food provision: 12
Local passenger transport 13
Building HVAC & lighting 21
Provision of other goods 37

Currently, all of mankind consumes ~2,300 GW’s worth of electrical power which works out to about 307 watts/person. However, like most of the things that determine human life styles, its distribution is extremely uneven. People in Scandinavian countries consume the most, about 2500 watts per person, followed by the USA and Canada’s ~1400 W. However, the majority of Latin America’s people consume less than 250 W, South Asia’s below 100 W, and Africa’s, fewer than 25 W. Over a billion people now don’t have access to electricity at all. If mankind is to prosper, clean, affordable and dependable (not intermittent) power must become available to everyone and it must be provided in a way that doesn’t pollute the air, poison the land, or change the climate.

Anyway, ~80 percent of the USA’s primary/raw energy is provided by fossil fuels translating to a mean per capita raw/primary energy consumption rate (power) of 9860 watts [99.5E+18J/3.15E+7/320E+6] or about eight [99.5/3.2E+8/570/7.5E+9] times that of the world’s average person today. Since one joule’s worth of raw/primary (heat) energy currently provides about 0.4 joules worth of useful “energy services” (the efficiency of most of fossil fuel’s applications is Carnot-limited) and Europeans apparently live almost as well consuming one-half that much raw/primary energy per capita, let’s assume that
supporting the life styles of each of the future’s equally EU-rich people would require ~2 kW’s [9860* 0.5*0.4 = 1972 ≈ 2000] worth of energy services (electricity). Consequently, a world with 11.2 billion such people must possess power plants able to supply an average power of about twenty two [11.2E+9*2000*3.15E+7/1E+12/3.17e+7 = 22.4] TWₑ (terawatt electrical). Finally, assuming that each individual region’s peak power demand is about 40% higher than its average and that no world-wide, zero-loss, “super grid” exists, our descendants would need ~30,000 [22.4*1.4*1012/109] one GWe power plants to live that well.

That power could not be generated with fossil fuels because even if there were enough of them (there isn’t\(^\text{18}\)), burning it would have catastrophic consequences. For example, the raw/primary (heat) energy represented by the world’s remaining 1139 billion tonnes of coal reserves, 187 trillion m\(^3\) of natural gas, and 1.707 trillion barrels of petroleum, (BP 2017) is about 5.0E+22 J’s which, if consumed by 40% Carnot efficient power plants, could generate 22 TWe for 29 years - ~35% of a typical first-world human life span. Additionally, those reserves collectively contain about 1200 Gt of carbon which, if converted to CO\(_2\) and dumped

\(^{18}\) We often see headlines announcing things like, “the USA has 7 to 9 trillion barrels of oil” which are apparently meant to reassure us that there’s nothing to worry about (Nextbigfuture 2012). However, if we bother to read beyond those headlines we discover that such oil is very “tight” and would be extremely difficult (expensive) to recover; meaning that perhaps one trillion barrels of it would be recoverable with today’s fracking technologies. However, we’re next assured that with “aggressive use of new fracking technologies combined with in situ ‘fire flooding’ and/or ‘water flooding’ ” perhaps 20-30% of it might be recovered. One trillion barrels of oil represents about 610 Exa Joules worth of raw heat energy which is equivalent to about one year’s worth of Mankind’s current, not a richer and more egalitarian future’s, energy demand.
into the atmosphere would push global warming well past any of the “tipping points” suggested by the world’s climate modeling experts\textsuperscript{19}.

In order to more clearly see what these facts and figures mean, it’s necessary to consider them on a longer time scale than that which we humans customarily employ. Figure 3 was excerpted from a paper written/delivered by the one of the petroleum industry’s most influential geologists (and, eventually, most influential gadfly), Professor M. King Hubbert, sixty three years ago (Hubbert 1956). It depicts Mankind’s total energy consumption extending from the dawn of recorded history 5000 years ago to 5000 years in the future assuming that population eventually stabilizes and we choose to replace finite fossil fuels with a sustainable (breeder reactor-based) nuclear fuel cycle before our civilization collapses. To Professor Hubbert, “on such a time scale, the discovery, exploitation, and exhaustion of the Earth’s fossil fuels will constitute an ephemeral event.”

\textsuperscript{19} Dr. Chris Turney’s “Ice, Mud, and Blood” (Turney 2008) is the best-written book I’ve read yet about how Mother Nature’s sundry “tipping point” mechanisms could convert “Global Warming” into “Global Catastrophe”.

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Unfortunately, because the world’s decision makers have been kicking the nuclear can on down the road for far too long, we’ll have to continue to seek, extract, and burn fossil fuels throughout much of the rest of this century. Of them, natural gas represents the best choice because it is relatively clean burning (little smoke), generates only about one half as much CO₂/Joule as coal, and is still in a relatively early phase of depletion. According to the German Federal Institute for Geosciences and Natural Resources, world cumulative natural gas production up to 2016 was 117 trillion cubic meters, world natural gas reserves were 197 trillion cubic meters, and resources were 643 trillion cubic meters (BGR 2017, Table A-15). "Resources" is defined as "proven but which cannot currently be exploited for technical and/or economic reasons plus unproven but geologically possible resources which may be exploitable in the future" (world natural gas 2018). The 197 trillion cubic meters of gas that we know for sure(?) could be recovered with current technologies ("reserves") represents 7.23E+21 Joules of heat energy which could produce about one half that much electricity. One year’s worth of 22 TWₑ electrical power equates to 6.94E+20 J meaning that
the world’s total gas reserves could power 11.2 billion EU-energy-rich people for 5.2 years while its burning kicks the atmosphere’s CO₂ concentration up by another ~50 ppm.

Because the half-life of CO₂ already in the atmosphere is about a half century (Moore and Braswell 1994), achieving the goals of the Paris climate accord (limiting maximum temperature rise to 1.5 ºC) at this late point in time would require an almost immediate switch to clean (no GHG emissions - see Fig. 2) energy sources and enough carbon dioxide removal (CDR) from that already in the atmosphere to reduce its concentration to ~350 ppm by volume (Hansen 2008). Consequently, some of the ICPP’s more optimistic post-COP 20 scenarios/reports assume that “bio-energy with carbon capture and storage” (BECCS) represents a magic bullet that could address both global warming and the future’s energy supply conundrum in a politically correct (no nuclear) fashion (Martin 2016). All such scenarios are unrealistic because raising sufficient switch grass, palm oil, wood, etc. would require vast amounts of land, water, and fertilizer that most people (especially the hungrier ones) would consider better-utilized if applied to producing something other than fuel. It is also unrealistic because carbon capture and sequestration (CCS) is intrinsically both difficult and expensive, which is why after several decades and many billions of dollars-worth of “study” and “demonstrations”, only about 0.08% of anthropogenic CO₂ is currently being so managed (CCS 2018). Finally, BECCS-based “save the world” scenarios are impossible because they don’t scale. For example, burning 100% of the world’s current annual grain (about 2.5 Gt, see Statista 2017) plus “bone dry wood” (about 1.9 Gt, see Wood 2018) harvests in “clean” (CCS equipped) 40% efficient (optimistic) heat-to-electricity power plants would generate useful energy services (electricity) equivalent to the output of ~935 one GWₑ (“full sized”)
nuclear reactors. That’s just ~3% of the number required to render 11.2 billion people one-half as energy rich as the USA’s citizens are now. Any backup system for low capacity factor energy sources (solar and wind) must be able to satisfy most, not 3%, of total demand. Furthermore, the carbon (about 1.8 Gt) in that much biofuel (primarily carbohydrate \(\approx (\text{CH}_2\text{O})_n\), heat of combustion \(\sim 15.5\text{E}+3 \text{ J/g}\)) represents only about 0.3% of mankind’s total anthropogenic carbon emissions to date, which means that even if 100% of the CO\(_2\) it represents were to be captured and sequestered, it wouldn’t make much difference. Consequently, because it could not achieve either of the IPCC’s goals and would surely compete with food, fiber, and construction-type wood production, all rosy primarily BECCS-based scenarios are hopelessly unrealistic and therefore do not “deserve further study” – the conclusion common to the majority of reports in almost every scientific field. Additionally, because growing biofuels removes inorganic nutrients and soil organic carbon, it’s just another extractive technology that would further degrade the environment while compromising food production (Lal 2008).

In my opinion, the most useful outcome of the climate science research performed to date is that global warming and ocean acidification/warming/pollution have been absolutely proven to be man-caused (Hansen 2008) and that reasonably consistent/accurate estimates of global carbon fluxes, sources, sinks, etc., have joined the tremendous amount of other technical information freely available on the internet. Such information along with readily available computerized spreadsheets renders it simple for anyone to evaluate any proposal described in a properly written/edited paper and thereby decide for themselves whether or not it is reasonable. I haven’t yet seen a
politically correct, peer-reviewed geoengineering proposal capable of passing such muster.

For example, GOOGLEing “oceanic acidification mitigation” brings up several fine-sounding electrochemical-based schemes published in peer reviewed journals and subsequently described in press releases. (APPENDIX XX presents a worked-out won example of how atmospheric CO2 influences oceanic acidification) A typical proposal invokes giant chlor-alkali cells which would electrolyze aqueous solutions of pure NaCl (natural seawater’s other components would plug up such cells) to generate sodium hydroxide that would then either be dumped directly into the ocean to counteract CO2 engendered acidification or utilized in gas/liquid contactors to scrub it from the atmosphere (House 2007 - see reactions below). The simultaneously produced hydrogen and chlorine gases would be recombined by fuel cells to recover some of the electrical energy required by the chlor-alkali cells

Electrolysis: \[2\text{NaCl} + 2\text{H}_2\text{O} \rightarrow 2\text{NaOH} + \text{Cl}_2 + \text{H}_2\]
Air scrubbing: \[\text{NaOH} + \text{water} + \text{CO}_2 \text{ in air} \rightarrow \text{NaHCO}_3 \text{ aq}\]
Energy recovery: \[\text{H}_2\text{Cl}_2 \text{ (fuel cell)} \rightarrow 2\text{HCl} \text{ (in a water-based electrolyte)}\]
\[\text{HCl}_{\text{aq}} + \text{a Mg/Ca-containing rock powder} \rightarrow \text{CaCl}_2 + \text{MgCl}_2 + \text{rock sludge}.\]

The fuel cells’ product, HCl (a strong acid), would then be neutralized via reaction with powdered mafic (basic) rock (e.g., basalt) in giant “pressure cookers” thereby generating a waste stream comprised of decomposed rock (mostly silica) slurried-up with a magnesium/calcium/iron/etc., chloride-salt brine. Of the numerous
“technical issues” raised by such proposals, I will just discuss their electrical energy demand. While this particular example was characterized as “energetically feasible”, real chlor-alkali cells require about 3.9 volts to operate at a reasonably productive rate (~ 0.5 A/cm²) and real H₂/Cl₂ fuel cells generate only about one volt at similarly realistic current densities. This means that the net energy required to produce one mole (or equivalent) of hydroxide would be 2.8E+5 J [1 equivalent*(3.9-1) volts * 96,500 coulombs/equivalent)*1J/(or volt*coulomb)]. Producing sufficient sodium hydroxide to deal with the amount of anthropogenic CO₂ that some of IPCC’s analysts apparently assumed could/would be sequestered via BECSS circa 2050 (~10 Gt/year) would require 6.36E+19J [2.8E+5 J/mole*(10E+9 t*1E+6 g/t)/44 g/mole]. If it is to be done within one year, the entire output of either ~2122 [6.36E+20 J/1 E +9 J/s (Watt)/3600 s/hr/24 hr/day/365 day/year/0.95] full-sized (~1 GWₑ 0.95 capacity factor (CF) nuclear reactors, ~4.5 million 1.5 MW-rated 30% CF, wind turbines, or ~21 billion, 1 kW-rated, 10 % CF solar panels would be required.

Such schemes could not be powered with fossil fuels either. For example, since the heat of combustion of average US coal is about 24,000 J/g and burning one gram of it generates about 2.7 grams of CO₂, generating sufficient electricity to implement the above example with 50% thermal-to-electricity efficient coal fired power plants would generate about 14 Gt of “new” CO₂ – 42% more than their power could sequester in that fashion.

Another well publicized electrochemical save-the-world scheme invoked scrubbing intrinsically acidic CO₂ from the atmosphere with a strongly basic ~750ºC Li₂CO₃/Li₂O molten salt electrolyte/adsorbent from which that carbon would be then electroplated-out/sequestered in
the form of graphite (Licht 2009). Since both the electricity required to reduce carbonate carbon to graphite and the heat needed to keep the electrolyte molten is to be provided with “solar towers”, it is/was eminently politically correct and therefore received a great deal of favorable mention. Unfortunately, because: 1) STEP’s (“a solar chemical process to end anthropogenic global warming”) sequestration mechanism requires four times as many electrons per carbon atom as does that of the above-described electrochemical proposal; and 2) scrubbing air with a molten salt would heat it to the latter’s temperature\(^\text{20}\), its total energy requirement would be ~four times higher if 90% of its process heat requirement could be recovered/recycled via heat exchangers and 19 times greater if it could not. If powered by the wind rather than solar towers, the latter figure corresponds to ~89 million 1.5 MW, 30% CF, wind turbines.

Schemes like those do not deserve “further study” regardless of who proposes them or how many warm and fuzzy renewable buttons they push.

The most alarming thing about how things have been going recently (see the Fourth National Climate Assessment - NCA4 2018) is that civilization remains absolutely dependent upon resources that will inevitably become prohibitively expensive when most of the cheaper/easier-to-access coal, oil, and natural gas have been consumed, which situation is likely to occur well before 2100 AD. Unless the

\(^{20}\)The heat capacity of air is ~1.05 J/g/degree. Consequently, the scrubbing of 10 Gt of CO\(_2\) from 400 ppmv air within one year would require heating ~1.37E+12 tonnes of air from ambient to ~750°C requiring ~1.05E+21 J of energy which figure corresponds to the full-time output of 33,300 one GW\(_e\) nuclear (or methane or coal or wood chip or switch grass…-fired) power plants.
world’s decision makers have already developed/implemented a simultaneously “clean”, reliable (not intermittent), and affordable alternative by then, civilization is apt to collapse, heralding the onset of a dark ages akin to that depicted in Mad Max movies.

2.2 This book’s technological fix’s specifics

Let’s do some more ball park calculations to demonstrate how Weinberg and Goeller’s vision could address some of Africa’s (and the world’s) energy-related issues.

First, let’s make some assumptions. To begin with, I’m (reluctantly) going to assume that the UN’s population projection for what’s apt to continue to be the world’s most needful region (Africa) – about 4.5 billion by 2100AD – turns out to be right.

Next, since my goal is to demonstrate what a nuclear renaissance should be able to accomplish with respect to assuring Africa’s (and also the rest of the future world’s) food security, I’m going to assume that part of the useful energy (electricity) it would provide is devoted to doing so – in other words, nuclear powered machinery would provide the water, fertilizer, and soil-building minerals required to render African agriculture sustainable.

Finally, I’m going to assume that Africa’s decision makers along with who/whatever else chooses to help/enable them decide that its citizens should enjoy the same living standards as do average EU citizens today.²¹

²¹ “The test of our progress is not whether we add more to the abundance of those who have much; it is whether we provide enough for those who have too little.” Franklin D. Roosevelt
2.2.1 Which food crops should our descendants raise and how much land would that take?

A recently leaked draft of an upcoming Intergovernmental Panel on Climate Change (IPCC)’s report about land use issues that’s scheduled to be released in September 2019, indicates that there’s now a near consensus by its climate modeling experts that it will be impossible to keep global temperatures at safe levels unless there is a transformation in the way that humanity produces food and manages its land (Guardian 2019). “We now exploit 72% of the planet’s ice-free surface to feed, clothe and support our population”, that report warns. Currently agriculture, forestry and other land use produces almost a quarter of greenhouse gas emissions.

Additionally, about half of all methane emissions, our atmosphere’s second most potent greenhouse gas, come from cattle and rice fields, while deforestation and peat land removal cause further significant carbon emissions. The impact of intensive agriculture – which has enabled the world’s population to soar from 1.9 billion a century ago to 7.7 billion today – has also increased soil erosion and seriously reduced the amount of organic material in the ground.

In the future this situation is apt to get worse. According to the IPCC’s experts, “Climate change exacerbates land degradation through increased rainfall intensity, flooding, drought frequency and severity, heat stress, wind, sea-level rise and wave action,” The aforementioned report is a pretty bleak analysis of the dangers ahead and comes at a time when rising greenhouse gas emissions have made news by triggering a range of severe meteorological events including

• Arctic sea-ice coverage reached near record lows during July
• The heat waves that hit Europe during that month were between 1.5C and 3C higher than they would have been if we had not used the atmosphere as a “repository” for our gaseous carbon emissions
• Wide spread burn offs of what recently used to be called the Amazon’s “rain forest”, and …
• Mean global temperature was bout 1.2C above pre-industrial levels

The last point is particularly alarming, because almost a decade ago the same experts had concluded that a temperature rise exceeding 1.5C risks triggering climatic destabilization while anything higher than 2.0 C renders it almost certain. Bob Ward, policy director at the Grantham Research Institute on Climate Change and the Environment concludes that “We are now getting very close to some dangerous tipping points in the behaviour of the climate” and also that “it is going to be very difficult to achieve the cuts needed to prevent it from happening.”

That IPCC report emphasizes that agricultural land will have to be managed more sustainably so that it releases much less carbon than it presently does. Peat lands will have to be restored by halting drainage schemes; meat consumption will have to be cut to reduce methane production; and food waste will have to be curtailed. Among the proposals put forward by that report is a major shift towards vegetarian and vegan diets: “The consumption of healthy and sustainable diets, such as those based on coarse grains, pulses and vegetables, and nuts and seeds … presents major opportunities for reducing greenhouse gas emissions,”. There also needs to be big change in how land is used. Governmental policies need to include “improved access to markets, empowering women farmers, expanding access to agricultural services and strengthening land tenure security, and Early warning systems for
weather, crop yields, and seasonal climate events must also be established.”

With these things in mind let’s try to come up with estimates of what my example’s population (Africa’s future citizens) should eat and how much land would be required to provide such food. Since vegetarian diets are much more efficient resource-wise than are those generally consumed by today’s richer people, for simplicity’s sake, I’ll assume that by 2100 AD everyone will be consuming 2500 kcal/day (1.05E+7 J), most of which is provided by two especially productive crops raised upon the minimum amount of soil capable of providing yields currently achieved in the USA.

A recent paper (Clark and Tillman 2017) discussing the amount of land (m²) to produce protein with different crops, USDA reports (http://usda.mannlib.cornell.edu/... ) of US crop yields/acre, and candidate food crop characteristics from various WIKIPEDIA entries suggest that an efficient combination would comprise maize (corn) because it’s exceptionally productive, nutritious, and already widely produced/consumed/accepted in Africa plus some sort of pulse (legume) to complement its unbalanced mix of amino acids (not enough lysine - Lal 2017). Of the likely pulses, peanuts seem to make the most sense because they are a “hot weather crop”, taste considerably better, contain more fat/oil, also already widely produced/consumed/accepted in Africa, and almost equally important, would not extract as much phosphorous and potassium (key macronutrients) from its soil per food-calorie as would the next runner-up crop, soybeans.

Assuming zero waste, providing 2500 kcal/day of food for 4.5 billion people translates to 4.1E+15 kcal (1.72E+19 Joule (J)) worth of foodstuffs per year. If we also assume that 75% of their food-type
calories are to be provided by maize, simple calculations indicate that the total amount of land required to feed every African person circa 2100 AD adds up to $9.71 \times 10^7$ hectare (ha), of which $7.28 \times 10^7$ ha would be devoted to maize and $2.43 \times 10^7$ ha to peanuts.

That combination of foodstuffs would provide everyone with 59 grams of “complete” protein per day along with virtually everything else that humans need to first grow up and then remain healthy. Africa’s folks would probably also want to (and should) devote perhaps an additional $5-10\%$ of similarly productive/managed land to raising the lower calorie/protein but tastier fruits, vegetables, and spices that render vegetarian diets far more palatable than most of the world’s “rich” people realize. Additionally, if Africa’s much more prosperous (on the average) future inhabitants were to decide that chicken should provide 20\% of their food calories ($500$ kcal/day/person – about fourteen times more than they currently consume), similar calculations suggest that roughly 10\% additional land would be required to raise the peanuts and maize needed to feed those birds as well. The substitution of the purportedly equally nutritious/delicious cricket “meat” (Van Huis 2012) for that chicken would require only about 5\% more peanuts/corn/land than would a strictly vegetarian dietary.

$9.71 \times 10^7$ ha is about the same amount of land that the USA currently devotes to producing all of the crops listed in Clark and Tillman’s

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24 Of course I’m just doing semi-quantitative theorizing here because people typically waste about one third of their food which means that my calculations similarly underestimate the amounts of land, water, fertilizer, etc. needed to feed their descendants. It’s probably also unreasonable to assume that the world’s agricultural entrepreneurs would ever permit their elected representatives to eliminate today’s lucrative bioalcohol, palm oil, and biodiesel subsidies.
paper to support ~320 million people (~7% of the number assumed herein for Africa circa 2100 AD). Thanks to artificial fertilizers, improved crop genetics, and pesticides, today’s modern farmers now need 68% less land to produce a given quantity of food than did their mid 20th century predecessors utilizing that era’s more “natural” (aka more “organic”) farming practices. A team led by Professor Andrew Balmford of Cambridge University recently showed that the best way for humanity to preserve the world’s biodiversity is to minimize the amount of land used to serve its own needs and thereby allow the set aside (“sparing”) of large areas capable of supporting natural lifeforms; i.e., the set aside of arable (“good”) land, not just more desert [Phalan 2011]. Heading off today’s ongoing “sixth extinction” will require efficient, energy intensive, farming, not switching back to inefficient natural/organic farming.

A FAO estimate (FAO 2002) of the area under “managed water and land development in Africa totals some 12.6 million ha, equivalent to only 8 percent of its arable land”. Since Africa’s total area is about 30.3 million km², this suggests that 1.58E+8 ha [12.6E+6 km²/100 ha/km²/0.08 or 5.2%] of it is considered to be “arable”. Since my estimate of the absolute total area required to feed its 4.5 billion future inhabitants (9.71E+7 ha) represents only 61% of that figure, hopefully, they will choose to continue to share some of their continent’s still-useful land with its iconic suite of wild animals.

2.2.2 The whys and costs of desalination
Like wind and solar power, water is a renewable resource with both highly variable and limited availability. Rainfall, temperature, evaporation, and runoff determine its total availability and human decisions determine who gets what. Nearly every country in the world
experiences water shortages during part of the year, and more than 80 of them suffer from serious water shortages. Clean water resources per capita are declining rapidly as human population increases. Population growth reduces water availability per person and stresses the entire environmental system. Pollution, erosion, runoff, and salinization associated with irrigation, plus the overall inefficient use of water, contribute to the decline in water resources. Allocation of increasingly scarce fresh water generates conflicts between and within countries, industries, and individual communities with the majority of it everywhere consumed by agriculture. Water shortages are also severely reducing biodiversity in both aquatic and terrestrial ecosystems (Pimentel et al. 1997).

Africa’s 4.5 billion(?) future inhabitants wouldn’t be able to feed themselves with ~60% (or all) of its arable land unless they become able to irrigate it. Because irrigated land almost always produces higher yields than do rain fed farms and permits double and sometimes even triple cropping in warmer regions, such lands provide around 40% percent of global cereal supply (FAO 2011a). currently Only ~4% percent of Africa’s cropland is currently irrigated due to prohibitive costs, insufficient water, and a general lack of commitment to infrastructure-related investment in things like power plants and the fuel needed to operate them. Consequently, it’s unlikely that this book’s cornucopian future would be implemented by either the African people themselves or the institutions/people that have provided most of their “aid” to date25. However, let’s pretend that will happen.

25 It really just boils down to human nature. Rich people usually have lots of alternatives and choose the cheapest way to solve their problem whereas poor people without such options have
Pumping water onto approximately 10 percent of the world’s total arable land (around 300 Mha) currently consumes around 0.225 EJ/yr. Another 0.05 EJ/yr of indirect energy is devoted to the manufacture and delivery of irrigation equipment (Smil 2008). Around two-thirds of the water currently used for irrigation is drawn from underground aquifers. Energy intensive electricity powered deep well pumping accounts for about two-thirds of that and projections suggest that it will become ~90% by 2050 when shallow reserves are almost totally depleted. Current aquifer water extraction rates exceed recharge rates – grossly so in many places. Additionally, global warming is simultaneously exacerbating droughts and melting the glaciers that feed the rivers providing much of the world’s cheap-to-deliver irrigation water. Global warming has caused Mount Kilimanjaro’s “snows” to disappear along with most of those within the USA’s Glacier National Park. Building more dams won’t solve such problems because dams do not create water. Additionally, a comprehensive review of Nigeria’s outside-funded dam projects (Tomlinson 2018) concluded that while they do make money for local promoters and the outsiders that fund/support them, they decrease net agricultural productivity by turning fertile downstream floodplains into deserts. In addition to killing wetland-dependent wildlife, those dams to live with theirs even if doing so will eventually kill them (who cares? - most poor people live” in ...thole countries” and aren’t the right color anyway). Building enough desalination facilities and their power plants to “save” the world’s poor people will cost several hundred $billion & it’s pretty darn unlikely that today’s venture capitalist dominated societies will ever do anything that doesn’t guarantee them and theirs a “reasonable” return on investment.

26 Dams have almost totally destroyed salmon runs throughout most of the “civilized” world including, of course, my home state of Idaho. Its trout streams have been further impacted by both warmer water and a myriad of tiny dams and extra diversions built to take advantage of the fact that low head hydropower plants are heavily subsidized. Other things that have served to devastate its trout fishing include the now almost universal use of neonicotinoid pesticides
have served to lower not raise, the incomes of far more people than have benefitted. Most such dams also don’t generate nearly as much electrical power as “promised” due to inadequate maintenance and low (water-limited) capacity factors. Finally, at best, dams represent a temporary fix for the problems that they are built to address because their reservoirs will eventually fill with mud.

Water shortages plus the high cost of desalination – primarily due to high electricity costs – has led some countries rich enough to do so (e.g., China) to reduce their own crop production and rely more heavily upon imported grains.

This situation is unsustainable which means that I’ll next assume that most of the water irrigating Africa’s future farmlands (and much of the rest of the world’s too) would be generated by desalinating seawater – the Earth’s only truly inexhaustible/sustainable water source. Wikipedia’s description of Israel’s solution to its water issues (Israel 2018), demonstrates how a properly managed future technological society could address the world’s water-related woes. Israel’s ~8.5 million people are fed by ~1.045E+9 m³ of fresh water applied to its mostly-irrigated farmland (Jewish 2016). This suggests that the rest of the even more water-stressed Middle East’s mostly-poor ~101 million people, including the majority of those living in Palestine, Iraq, Jordan, Lebanon, Oman, Syria, and Yemen (Demographics 2018), could be equally well supported by irrigating their potentially arable land (assuming all of it) with 1.24E+10 m³ of desalinated seawater.

(Mason 2013) and refusal to enforce a law requiring irrigation canal companies to screen their headgates (Barker 2015).
Assuming the ~3 kWh/m³ energy requirement (RO 2018) of today’s most popular approach to desalination, reverse osmosis (RO), doing so would require an energy input of 1.34E+17 joules/a, which corresponds to the full-time output of ~4.2 one-GWₑ nuclear reactors. The volume of water corresponding to adding 0.51 meter (20") of it over 9.71E+7 ha of African farmland is 4.93E+11 m³, which, if generated via RO, would require the full-time output of ~169 full-sized nuclear reactors (5.33E+18 Je/a). In principle at least, Siemen’s electro dialysis-based desalination technology would require only about one-half that number of reactors and is also less apt to become fouled by seawater’s other-than-salt impurities (Hussain & Abolaban 2014).

To continue, Africa’s average elevation is about 600 m (2,000 feet) above sea level, roughly the same as that of both North and South America. Assuming that all of Africa’s desalinated irrigation water would have to be pumped uphill that far, the energy needed to do so would be 2.90E+18 joules [4.97E+11m³*1000 kg/m³* 600 m*9.8 m/s] requiring another 92 full-sized power plants.

How much would Africa’s desalination equipment cost? The contractual cost of the world’s (Saudi Arabia’s) biggest (~one million m³/day), RO-based desalination plant is $1.89 billion (Desalination 2018). Collectively, these numbers suggest that building enough RO plants to irrigate Africa’s future farmlands would require a one-time capital expenditure of $2.55 trillion [4.93E+11*0.00189/(365*1E+6)] – about 11% of the USA’s current national debt. Similarly addressing California’s Central Valley’s chronic irrigation water problems should cost only about $40 billion.

As mentioned earlier, the Western World’s recent Middle East military incursions will probably end up costing its citizens ~thirty times more ($4-6 trillion) than it would to have built enough nuclear powered
desalination plants to provide sufficient fresh water for everyone living there and thereby address a root cause of that region’s almost perpetual turmoil. For example, a recent paper in the Proceedings of the (US) National Academy of Sciences (Kelly et al, 2014) points out that the chief driver for today’s Syrian conflict is the unrest/poverty generated by relentlessly worsening droughts, not a desire for “regime change”.

Another plus for desalination is that its product does not add additional salts to soil and is also better at remediating already over-salinized soils than is ground water. A final plus is that because it doesn’t already contain near-equilibrium levels of calcium, magnesium, carbonate/bicarbonate, silica, etc., it is a better rock solvent (more corrosive) than is ground water. The next section will reveal why this is important.

2.2.3 Fertilizers

Another reason that the productivity of Africa’s farmlands is considerably lower than that of more developed regions is that relatively little fertilizer is used. The three most important components of fertilizers (macronutrients) include nitrogen in either its negative three (ammonia-type) or positive five (nitrate-type) oxidation states, potassium (invariably in its plus one oxidation state), and phosphorous (invariably in its plus five oxidation state). Nitrogen fertilizer production currently accounts for about one half of the fossil fuel (mostly natural gas) used in primary food production.
2.3.3.1 Nitrogen and the cost of fixing enough of it to feed everyone

We’ll start with nitrogen. US farmers hoping to produce 13.1 t/ha (200 bu/acre) of maize (corn grain) are advised to add ~ 258 kg of N/ha (PSU 2018). Since peanuts (a legume), can recover/fix its own nitrogen from air, much less nitrogenous fertilizer would be needed for land devoted to its cultivation – let’s say 50 kg N/ha. Assuming those application rates, fertilizing Africa’s future crop land would require ~ 2.0E+7 tonnes of ammonia each year (one kg N ≈ 1.21 kg of ammonia) An up to date estimate (thyssenkrupps 2019) of energy costs concludes that each tonne of ammonia made with electrochemically-generated hydrogen, pressure swing-generated atmospheric nitrogen, and conventional Haber Bosch processing equipment would require about 10 MWh’s \[10*3.6E+9 \text{ J}\] worth of electricity\textsuperscript{27}. That, in turn, suggests that satisfying this scenario’s nitrogenous fertilizer requirement would require the full-time output of ~23 one-GWe power plants.

2.3.3.2 The reasons why powdered basalt should supply the necessary and potassium

Since…

- Much of Africa’s (and the rest of the world’s) farmland has already lost a great deal of its topsoil via erosion.
- Much of its remaining topsoil is mineral-depleted.

\textsuperscript{27} Roughly 50% of all ammonia is currently combined with CO\textsubscript{2} to make urea. That CO\textsubscript{2} is re-emitted to the atmosphere when that fertilizer is applied to soils.
• Basic (mafic) rock-weathering is how Mother Nature limits the Earth’s atmospheric CO$_2$ concentration (figure 6) via “mineralization”,
• Basaltic rocks are both intrinsically basic (contain a good deal of magnesium and calcium) and rapidly weathered by the natural phenomena extant in cultivated soils (Moulton 2000),
• Most of the Earth’s crust consists of basaltic rock, a good deal of which is either on or close to the surface of its continents,
• Basaltic rocks contain relatively high concentrations of potassium and phosphorous along with all of the other biologically important elements which explains why soils comprised primarily of weathered volcanic ash most of which originally consisted of molten basalt are exceptionally productive (Beerling 2018),

…we’ll next assume that the phosphorous and potassium required to produce Africa’s food crops circa 2100 AD will be provided by amending its farmland with powdered basalt. In order to be effective, any such amendment must weather rapidly enough to release sufficient potassium and phosphorous to support high-yield
Figure 6: The Earth’s carbon cycle (commons Wikipedia.com)

agriculture which, in turn, means that the raw silicate rock surfaces must be “fresh” (not already equilibrated with the atmosphere and thereby covered/blockaded with secondary phases), ground to a considerably smaller particle size than is the quarry waste-type soil amendment rock powder currently being marketed to hobby farmers, and also mixed with root-zone topsoil, not just dumped upon the surface of the ground (Campbell 2009 and Priyono/Gilkes 2004). Based upon the rather limited amount of scientifically planned/supervised experimentation described in the open-access (not paywalled) technical literature, I’m next going to assume that this would require grinding it so that the particles comprising >80% of it possess diameters <10 microns. Since rock grinding is highly energy intensive – much more so than is simply recovering it from a quarry’s rock outcrop or waste dump – the cost estimate for this part of my scenario will be based upon that step’s
energy demand plus the resulting powder’s transport and distribution costs.

First, how much powdered rock must be made? The food stuff P and K concentrations, land areas, and crop yield figures in the papers referenced earlier suggest that the food consumed each year by Africa’s 4.5 billion future inhabitants would contain 2.64E+9 kg of potassium and 2.05E+9 kg of phosphorous. Assuming (wrongly I hope, but consistent with the way that things usually happen) that neither nutrient is subsequently recycled back to the soil (composted nightsoils?), both must be replaced each year via basalt weathering. The compositions of flood basalts vary considerably but since all originate from the Earth’s fairly well mixed underlying magma, for the following estimates I’m going to assume a composition with which I’m familiar (Leeman 1982 and Siemer 2019) – that of the basalt comprising Idaho’s “Craters of the Moon” National Monument and covering much of the rest of Idaho’s Snake River Plain. It contains an average of 0.61 wt% K$_2$O and 0.55 wt% P$_2$O$_5$ which translates to requiring 5.21E+8 tonnes of it per year to provide this scenario’s potassium and 8.69E+8 Mg to supply its phosphorous. Since phosphorous happens to be the limiting nutrient in this example, at steady-state, we’d be adding 8.95 tonnes [8.69E+8/9.71E+7] of powdered basalt/ha/a.

A review of rock grinding technologies (Jankovic 2003) suggests that producing one Mg of <10 micron basalt powder would require about 100 kWh’s worth of electricity. If so, making 8.69E+8 tonnes of it would require 3.13E+17 J, which if done throughout one year would require the full-time output of 9.9 one-GWe nuclear reactors.

If that powder were to be transported an average of 1930 km (1200 miles) from mine-to-farm via an electrified rail system as energy-efficient as that currently used to move US coal (185 km/L diesel
fuel/short ton), its energy cost would be about 6.80+16 J (assumes 1.1 Mg/short ton, 33% heat-to-mechanical engine efficiency and 44.5 MJ/kg diesel fuel with a SpG of 0.85). Trebling that figure to account for fuel consumed by trucks and tractors at the rail heads, brings the total to 2.04E+17 joules/a, which corresponds to an annual transportation/distribution energy demand requiring another 6.5 one-GWe nuclear reactors to satisfy.

An application rate of 8.95 tonnes/ha/a is not really very large because it represents only about 0.5% of the mineral matter already within a six inch deep (typical annual crop root zone) layer of normal density/composition topsoil and is also considerably less than what conventional tillage-based farming practices often lose via wind/water erosion (typically about 30 t/ha/a - Pimental 2009). Consequently, since my scenario’s rock grinding/distribution costs are much lower than its irrigation water and nitrogenous fertilizer costs, it would be a good idea to at least start out with considerably larger powder application rates, perhaps 40-50 tonnes/ha. Doing so would also reduce the chance of crop “starving” due to slower-than-assumed weathering rates.

The 300 [169+92+23+9.9+6.5] GW_e’s worth of “clean” power plants required to implement the agricultural aspects of the above-described African scenario’s clean/green utopian future is about the same amount of power currently generated by all of the world’s nuclear reactors and about four times greater than Africa currently produces in any fashion (about 650 TWh, see Energy in Africa 2018). However, it represents only ~3% of the total energy services required by 4.5 billion people as rich as the EU’s are now.

All of the necessarily huge machinery and manufacturing facilities required to implement this or any other technological fix capable of “saving the world” would be much cheaper to build and operate much
more efficiently with reliable power than with that provided by intermittent sources. While it would indeed be “possible” to run desalination/ammonia plants, rock crushers, tractors, locomotives, etc., with windmills and/or solar panels, doing so would be expensive, dangerous, and frustratingly unproductive to such machinery’s owner-operators and their customers. It would also require that $1/\text{CF}$ times as much machinery be built to do the job at the same rate that a $\text{CF} \approx 1.0$, MSR-powered world could: typically ~$3$ times as much machinery for wind and $4$–$10x$ as much for solar-sourced power.

Again, intermittent power supplies are suitable for some niche applications (e.g., charging a terrorist’s cell phone), not for powering technological civilizations (Brook 2018). That’s why today’s farm tractors, locomotives, container ships, cruise liners, and air liners are fossil fueled, not wind powered.

Also again, the above derived ball park numbers are just approximations because the rate and degree to which powdered basalt would release its constituents (weather) under field conditions is affected by a host of factors/variables. A nutrient-specific discussion of some of them may be found in a FAO report describing the use of raw phosphate rock as fertilizer (Zapata and Roy 2004). Thankfully, that subject is beginning to receive a good deal of attention (Taylor 2017) and some hopefully realistic experimental studies have begun (Beerling 2018).

Of course there’s more to implementing a sustainable agricultural system than just doing what I’ve suggested above. Soil conservation invokes three guiding principles: don’t till the soil more than absolutely necessary, keep it covered, and keep its crops diverse. Reduced tillage preserves pathways forged by the roots of preexisting plants, insects, and earthworms. Those pathways comprise porosity which allows the ground to store water for use in dry times and soak it up more effectively during
floods. Cover crops, like alfalfa, clover, and sorghum, keep the soil loose after the cash crop has been harvested and suppress weeds. When they become part of the soil during its preparation for planting crops like corn, wheat, rice and peanuts, they increase soil moisture and enhance yields. Since they keep the field's soil covered and preserve its porosity, cover crops also reduce its chances of being blown away by wind or carried off by sudden flooding due to heavy rainfall. Planting diversely prevents the nutrient drain occurring when the same crops are grown season after season. Rotating through different varieties acts rather like multivitamins, adding a variety of nutrients to the soil over time. When necessary, drought-resistant crops (e.g., cowpeas instead of peanuts) could save water, and use that which is already present more efficiently. Soils would also be conserved by diversifying portfolios. Farmers might plant several kinds of crops in one area and keep livestock on another so that extreme weather shifts would not put their entire enterprise at risk.

Recycling K & P back to such soils in the form of composted human waste would also greatly reduce their powdered rock requirement. If all of these “good practices” were to be implemented, high tech/high yield farming would require less energy than my examples have indicated.

2.3 The reasons why politically correct renewables couldn’t “save” Africa

Assuming that “energy services” means electricity (reasonable because most of its applications are nearly 100% efficient) and that no worldwide, zero loss, (magic) power grid has been built, generating Africa’s share of the world’s total energy/power supply would require about 12,000 [30*4.5/11.2*1012/109] full-sized (~one GWe) breeder-type (“renewable”) nuclear power plants generating an average output of 9 TWₑ [4.5E+9*2 kW].
The following example demonstrates why today’s most popular alternative/renewable energy sources could not meet that demand.

First, let’s see how many of today’s purportedly “cheap”, roof top-type, solar panels would be required to produce future Africa’s 9 TW_e’s worth of useful energy. At Home Depot (Dec. 2018) one can purchase four, real state of the art (19% efficient), 265 watt-rated, 1.61 m^3 (39” by 65”) solar panels for $1412. If they were to be employed in Nigeria, which purportedly exhibits an average solar irradiance of 5.5 kWh/m^2/day (Ojuso 1990), each of those panels would generate a time-averaged power of 70.1 Watts \[1.61*0.19*5500*3600/(24*3600)\] which means that their “capacity factor” (CF) when so-situated would be 26.4% \[70.1/265\]. That CF is about two and one-half times greater than if such panels were installed in northern Europe and ~50% greater than that anticipated by South Africa’s energy experts circa 2050 (Table 3).

Anyway, that CF suggests that powering Africa’s 4.5 billion future citizens with them would require 128 billion \[9000E+9/70.1\] such panels costing about $45 trillion of today’s dollars. Since such power is ineluctably intermittent (unreliable), they would also have to buy enough batteries to keep things running during the roughly 73.6% \[100-26.4\] of the time that their solar panels would not be producing much. How many batteries would that be? Assuming that Africa’s future inhabitants decide that they could get by with just 1 day’s-worth of energy storage (that’s not conservative- widespread cloudy and windless periods often last longer than one day) they would have to build/buy about 216 billion kWh’s worth of storage capacity \[2000 J/s*4.5E+9*3600 s/hr*24 hr/day/3.6 E6 J/kWh = 2.16E+11 kWh\], which, if implemented with Tesla’s equally real and state-of-the-art 13.5 kWh, ~$7000, lithium ion battery "Power Walls", would cost today's subsistence farmers’ hopefully much more prosperous descendants another $100 trillion
[$7000/13 \text{kWh}\times200\text{E+9 kWh}/3.6\text{E+6 J/kWh}] \text{ of today’s dollars to purchase the first time around (lithium ion batteries only last for a few years).}

For this sort of application Li ion batteries don’t scale for several reasons one of which has to do with their most expensive component, cobalt.

When a Li ion battery charges/discharges, the cobalt within its cathode shifts back and forth between its tri and quadrivalent oxidation states.

Since …

- a lithium ion battery’s voltage is about 3.5
- one equivalent ‘s worth of charge is 965000 coulombs (one Faraday), and
- cobalt’s equivalent weight for this reaction is 58.9 grams

…one kWh’s worth of storage would require an absolute minimum of 621 grams $[3.6\text{E+6}/96500*58.9/3.5]$ of cobalt. One day’s worth of 9 TW power storage adds up to 1.58E+11 kWh which translates to a cobalt requirement of 1.35E+11 kg. Last year’s (2018) total world cobalt production was about 1.5E+8 kg or just 0.11% of this particular “what if’s” requirement for it.

Real world windmills exhibit similar capacity factors meaning that if they were to be used instead, a similar amount of energy storage capacity or some other sort of clean backup power would be required. Natural gas – today’s primary backup for wind and solar power plants – will probably be prohibitively expensive by then because all of the “cheap” natural gas will have already been discovered/fracked/consumed. Leaving it in the ground along with most
of the world’s remaining coal and oil would be a very good idea because burning them would otherwise add to the already excessive amounts of anthropogenic greenhouse gases (GHGs) responsible for climate change – coal as CO$_2$ and methane both as-is$^{28}$ and after it’s been oxidized to CO$_2$.

The above-derived numbers are actually somewhat optimistic because Africa is a better site for most today’s renewable energy sources than is much of the already-developed world. For example, by 2014 European Union countries had invested approximately €1.1 trillion (about 1.4 $trillion) in large scale renewable energy installations – mostly wind turbines and solar panels. That money provided a nominal nameplate electrical generating capacity of about 216 Gigawatts, nominally ~22% of total current European energy demand (~1000 Gigawatts). Data supplied by Europe’s Renewables Industry indicate that its total output throughout 2014 averaged 38 Gigawatts (~ 3.8% of Europe’s electricity requirement) at a combined mean capacity factor of ~18%. When adjusted for that factor, the capital cost of Europe’s wind/solar energy installations was €29 billion/GWe - about 30 times that of its conventional gas-fired electricity generation facilities and 3–10 times greater than GEN III nuclear power plants.

$^{28}$ While carbon dioxide is typically painted as the bad boy of greenhouse gases, methane is initially about 100 times more potent as a heat-trapping gas and several percent of that currently being fracked leaks directly into the atmosphere (Alvarez 2012). Any gaseous substance’s mass-wise Global Warming Potential (GWP) relative to CO$_2$ depends on the timespan over which that potential is calculated. A short half-life gas which is quickly removed from the atmosphere may initially have a large effect, but over longer time periods, become less important. Thus methane’s GWP over 100 years is about 34 but 86 over the first 20 years. Agriculture’s contribution to anthropogenic GHG emissions (~9%) is primarily due to methane (cow farts/burps, rice fields, etc.), not the CO$_2$ emitted by farm machinery engines.
Since the output of most renewable energy plants depends upon the season, local weather conditions and what time of day it is, their contribution to the electricity grid is erratic, intermittent, and non-dispatchable. This means that they often can’t contribute to supply when it’s needed, thereby rendering them useless (decorative?) much of the time. On the other hand, rules mandating use/priority of renewable electricity cause major grid disruptions when their output suddenly rises because dispatchable thermal (fossil fuel and nuclear) power plants must be cut back to a zero-efficiency “idling” state. Consequently, despite virtually no fuel costs, according to US EIA, renewable energy installations data can still cost up to 1.5 – 2.5 times as much to operate and maintain as do conventional gas fired power plants.

Figure 4: Germany’s real time wind power generation throughout 2014 Source: http://www.vernunftkraft.de/85-prozent-fehlzeit-windkraftanlagen-sind-faulpelze/
The red line across the top of Figure 4 was Germany’s wind power “capacity”\(^{29}\) that year – the blue spikes under it represent total power actually produced. That system’s capacity factor (energy produced/nameplate capacity) was about 0.16 and there were many times when essentially no power was generated across the entire country.

Figure 5: Typical variations in wind power generation on different geographical scales (figure courtesy of Juha Kiviluoma)

The leftmost figure of Fig. 5 displays one week’s worth of European wind power data during 2010. The right shows two years (2010 and 2011) of hourly data sorted by generation level. The aggregated generation for four European countries was created by calculating a weighted average of the capacity factor for each hour (Germany’s weight was three because it is a bigger country; the others were assigned a weight of one).

\(^{29}\) nameplate capacity is the figure usually quoted by wind & solar power salespersons & enthusiasts
South Africa’s future plans (World Nuclear 2019*) predict that by 2050 its electrical supply will be as follows: 20.4 GWe of nuclear capacity (up from today’s ~1.8 GWe) is to supply 30% of its electricity from 14% of the country’s total generating capacity, coal will generate 31% from 18% of total capacity, wind 18% from 37.4 GWe of capacity, and 6.5% from 17.6 GWe of solar PV capacity (the rest of its electricity, about 14%, will primarily be imported hydropower). Combining those numbers tells us that South Africa’s total anticipated generating capacity by then will be about 161 GW \[20.4/0.14/0.9\] where 0.9 approximates a LWR’s CF – over three times today’s - and the relative capacity factors for those sources will be as listed in the third column of Table 3.

**Table 3: South Africa’s electrical supply circa 2050**

<table>
<thead>
<tr>
<th>Source</th>
<th>%Energy delivered/%capacity</th>
<th>CF/CF nuke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear (GEN II or III LWRs)</td>
<td>2.143</td>
<td>1</td>
</tr>
<tr>
<td>Coal fired thermal</td>
<td>1.891</td>
<td>0.882353</td>
</tr>
<tr>
<td>Wind</td>
<td>0.481</td>
<td>0.224599</td>
</tr>
<tr>
<td>Solar PV</td>
<td>0.369</td>
<td>0.172348</td>
</tr>
</tbody>
</table>

(based upon figures from World Nuclear 2019*)

“Unfiltered” data like those in Figs 4 and 5 demonstrate why it is both irresponsible and callous for some of the “first world’s” energy experts to continue to insist/pretend that any combination of intrinsically unreliable renewable energy sources – windmills, solar panels, etc. – could provide the energy required by 11.2 billion people possessing a fair/equal share of a totally connected, cleaned-up, and “rich” technological civilization.
While it would be possible for “rich” people living in temperate climates to be comfortable when they’re within their well-insulated, properly windowed/oriented homes outfitted with especially efficient appliances and 7-20 thousand dollars’ worth of “Power Walls”, the technological civilization that they would depend upon for everything else (transportation, manufactured goods, and food) will require reliable, not intermittent, power.

Chapter 3.  A sustainable nuclear renaissance’s other “killer apps”

3.1 Atmospheric carbon sequestration

Let’s begin this section with another especially revealing ball park calculation:

Wikipedia entries tell us that the genuine climate experts have concluded that the effect of doubling the atmosphere’s CO$_2$ concentration corresponds to a forcing factor of $\sim 3.7$ Watts/m$^2$ at the earth’s surface.

There’s also a scientific consensus that mankind has dumped about 580Gt of carbon into the atmosphere since the beginning of the industrial age and that it’s apt to cause a mean global temperature rise of from 1.5 to 4.5 Centigrade degrees – for the purpose of this example, let’s say 3 degrees/doubling.
If we assume that that carbon was all derived from burning petroleum with composition \((\text{CH}_2)_x\), that’s about 677 Gt \([580*14/12]\) tonnes of it.

At 42 MJ/kg, the heat energy we got by burning it comes to \(~2.84\times10^{22}\) Joules.

Today’s \(~410\) ppm atmospheric \(\text{CO}_2\) concentration corresponds to about 46% of a doubling of the world’s pre-industrial, \(~280\) ppm level.

Since the Earth’s surface area is about \(5.2\times10^{14}\) m\(^2\), that corresponds to an anthropogenic carbon heat input rate of \(7.17\times10^{14}\) W \([0.46*3.7*5.2\times10^{14}]\).

The point of this little exercise was to show that any such fuel’s “bad” energy effects would exceed its “good” energy effects (the reason why we burned it) within \(~0.98\) years \([8.85\times10^{14}*3.15\times10^7\ s/a/2.84\times10^{22}\) Joules] and is likely to continue to do so for at least another 50 years (the “half-life” of \(\text{CO}_2\) in the atmosphere).

Energy generated building/using nuclear power plants results in the release of relatively little GHG/J – considerably less than that generated with wind turbines or solar panels (Fig. 4) – and the future’s more thermally efficient and more compact reactors would generate even less.
The speediest drop in greenhouse gas pollution on record occurred in France in the 1970s and ‘80s, when it transitioned from burning fossil fuels to nuclear fission for electricity production which lowered its greenhouse emissions by roughly 2 percent per year.

According to James Hansen et al. (Hansen 2013) the task facing the entire world today is more difficult because “emissions reduction of 6%/year plus 100 GtC storage in the biosphere and soils are needed to get CO\textsubscript{2} back to 350 ppm, the approximate requirement for restoring the planet’s energy balance and stabilizing climate this century”. His colleague & coauthor, Jeffrey Sachs, director of the Earth Institute at Columbia University says that, "On a global scale, it's hard to see how we could conceivably accomplish this without nuclear".
It been known for almost two centuries that the ultimate sink for the atmosphere’s carbon dioxide is basaltic (basic) crustal rock which, when exposed to atmospheric CO$_2$ and moisture, eventually weathers to form the miscellaneous oxides, clays, feldspathoids, and carbonate minerals that make up much of the inorganic components of soils (Ebelman 1845). Soil holds more than three times as much carbon as the atmosphere (Kramer 2017), yet its potential for deliberately reducing atmospheric carbon-dioxide levels (CDR) and thereby mitigating global warming, although much studied, is not being exercised (Beerling 2018). When completely weathered by those mechanisms collectively responsible for it in biologically active soils, each gram of my example’s basis basalt (10.06 wt% CaO and 7.65 wt% MgO) would release 7.35 milliequivalents \[ 0.1006*2/(40+16)+0.0765*2/(24.32+16) \] worth of base. If we assume that such base would convert acidic soil-gas CO$_2$ that would otherwise transpire (to the atmosphere\textsuperscript{30}) to the bicarbonate anion (Hartmann 2013), the application/weathering of 8.95 t/ha of such basalt over 9.71E+7 ha of African farmland would remove/sequester 0.076 Pg (76 million tonnes) of carbon. That sounds like a lot of “sequestration” but represents only ~ 0.009% of that currently in the atmosphere (~ 3300 Gt CO$_2$).

\textsuperscript{30} This phenomenon is termed “respiration”. It does not necessarily represent a net transfer of carbon from soil to atmosphere because it is largely offset by vegetative carbon inputs to soils. It is biologically driven (plants suck CO$_2$ down into the soil) and currently releases about eight times as much CO$_2$ to the atmosphere as does our fuel burning (Carey 2016). However, it is soon apt to be releasing much more because global warming is upsetting its normal equilibrium especially in the Arctic. Many scientists believe that a catastrophic “tipping point” is imminent.
If carbon sequestration is to become a primary goal, another way to go about doing it would be to convert corn stover and peanut hulls/stems (their leaves would probably end up on the ground) to “biochar”. Assuming this scenario’s African grain crops, that translates to converting about ~11.6 tonnes of biomass to ~3.1 tonnes of biochar and 5 tonnes of bio oil per ha (Extension 2002 and Fortress 2011). Because biochar is ~70% elemental carbon, burying it would simultaneously increase Africa’s soil’s organic matter (SOM) and sequester atmospheric carbon at the rate of ~0.25 Pg (250 million tonnes) per year.

If everyone in the world circa 2100AD – not just Africans - were to char their stover and fertilize with Snake River Plain basalt at the rate determined above, they would collectively sequester the equivalent of about 3 Gt CO₂ per year. However, since the atmosphere already contains about 500 Gt of excess CO₂ [((~412ppm-350ppm)/412ppm*3300 Gt =496] and will surely get further unbalanced before we kick our addiction to fossil fuels, it would probably take over two centuries for the future’s farmers alone to reduce it to a “safe” (350 ppm) level. This, of course, suggests that along with stopping atmospheric pollution and switching to the Earth’s most natural fertilizer, a “nuclear clean new deal” must accomplish something else as well.

What would that be?

The Earth’s oceans have become an especially tragic “commons” with respect to the impact of CO₂ dumping (Orr 2005) via acidification and

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31 Stover is above-ground, not-grain, crop matter - there’s generally about as much of it as grain and approximately 80% of it can be readily collected.
oxygen loss due to water-warming. (see APPENDIX XX). This is killing a host of pelagic creatures with aragonite (calcium carbonate) skeletons/shells all of which depend upon oceanic chemistry (pH and temperature) remaining as it has been for ~50 million years. These calcifying creatures constitute the Earth’s dominant natural CO$_2$ sequestration mechanism, converting ~1 billion tons of CO$_2$ each year to oceanic sediments$^{32}$ and limestone (coral reefs). Land plants and soils don’t come close because when today’s farmed soils aren’t amended with something like powdered basalt, soil microorganisms actually add (via respiration) net GHG to the atmosphere via their metabolism of soil organic carbon derived from the plants grown in them. Modern civilization’s sudden conversion of the Earth’s fossilized carbon to atmospheric CO$_2$ is driving oceanic extinctions that will eventually eliminate species ranging from coccoliths to whales, and thus about 15% of all human food protein.

A relatively inexpensive and practical way to address those effects would be implement the suggestion proffered by Professor Schuiling and his colleagues well over a decade ago (e.g., Schuiling & Krijgsman, 2006): i.e., crush basalt, or maybe even better, dunite (it’s more basic$^{33}$), into coarse sand-sized particles and scatter it/them along coast lines and

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$^{32}$ About 80% of the carbon stored in the geosphere is limestone and its derivatives formed from the sedimentation of calcium carbonate stored in the shells of marine organisms. The remaining 20% is stored as kerogens/oil/gas etc, formed through the sedimentation and burial of terrestrial organisms under high heat and pressure (Berner 1999).

$^{33}$ Dunite is an ultramafic plutonic rock possessing a chemical composition (majors only) falling somewhere between pure forsterite (Mg$_2$SiO$_4$) and pure fayalite (Fe$_2$SiO$_4$). High magnesium dunite is about four times as basic as is typical flood basalt. It’s a better CO$_2$ absorber but a poorer fertilizer.
shallow reefs. When so situated, natural wave action would greatly accelerate such sand’s weathering and thereby immediately relieve over-acidification while rendering the oceans better sinks for CO$_2$ and thereby affecting its removal from the atmosphere as well.

Another and maybe more effective driver for the implementation of Drs. Schuiling & Krijgsman’s proposal is that a global sand shortage has come to be because construction industries use it to make brick, asphalt and concrete – especially in and around Southeast Asia’s burgeoning urban areas. Consequently, vast amounts of it is being “stolen” from beaches and river banks at the same time that rising sea levels and climate change-induced river flooding is increasingly threatening homes and businesses situated in the denuded areas. That’s apt to render artificial basalt/dunite sand valuable enough to tempt entrepreneurs to make/sell lots of it when power becomes cheap enough.

Saving especially valuable waterfront-situated homes & hotels is apt to be at least as strong a motivator to important people and their elected representatives as is making everyone equally energy “rich”, rendering agriculture sustainable, and/or protecting any sort of commons.

Other ways that this book’s suggestions would mitigate the Earth’s excessive CO$_2$ issues include the cement/concrete-related suggestions discussed in section 3.3.

3.2 Nuclear powered transportation

3.2.1 Requirements

“The automobile is especially addictive...it is a suit of armor with 200 horses inside, big enough to make love in. It is not surprising that it is popular. It turns its driver into a knight with the mobility of an aristocrat
and, perhaps, some of his other vices. The pedestrians and people that use public transportation are by comparison, peasants looking up with almost inevitable envy at the knights riding by in their mechanical steeds. Once having tasted the delights of a society in which almost anyone can (pretend to) be a knight, it is hard to go back to being a peasant. Kenneth Boulding

Much of what people in today's richer countries have come to take for granted depends upon a world-wide transportation system that will suffer from price shocks and shortages as petroleum production inevitably peaks out and then declines. Petroleum still provides about 40% of the world’s total primary energy supply, the largest share. Changes in its price and availability will have tremendous impact worldwide because alternative sources don’t contribute much to the world’s transportation sector. Petroleum production will decline due to the same natural laws underlying everything. It is often claimed that Hubbert’s “peak oil” concept – the fact that oil production via any means from any/all sources will reach a maximum level then decline, – is only about geology. In fact, it is a consequence of geology, reservoir physics, economics, government policies and politics. Their intrinsic limitations will eventually affect all human activities because neither economic incentives nor political will can break or even bend them. Several natural depletion mechanisms affect petroleum production. Depletion-driven decline occurs during the primary recovery phase when decreasing reservoir pressure leads to reduced flow rates. This phenomenon is especially prevalent in fracked-type oil and gas wells. The secondary recovery phase involves water injection to maintain pressure but increasingly more water and less oil is recovered over time. Additional invested capital and technologies, e.g., CO₂ injection, can enhance oil recovery in a tertiary recovery phase but it comes at a still higher cost. It’s like squeezing water out of a soaked sponge – easy to
begin with but increasing effort is thereafter required for diminishing returns. Eventually, squeezing a sponge or oil basin harder isn’t worth the cost/effort and will inevitably cease.

Another natural analogy is the relationship of predator to prey populations: “easy” oil leads to increasing profits and therefore further investment in extraction capacity (easy mice means more kittens). The easiest (typically the largest) resource reservoirs are inexorably depleted – slowly with “conventional” oil wells, quickly with fracked ones. Extraction costs in terms of both energy and monetary inputs rise as production moves to lower quality deposits. Eventually, investments can’t keep pace with rising costs, declining production from mature fields cannot be overcome and total production begins to fall.

Additionally, regardless of capital availability or increasingly high prices, at some point, an oil well can no longer deliver net energy (most of the cats along with their kittens die). In 1982, U.S. petroleum geologist M. King Hubbert said: “There is a different and more fundamental cost independent of the monetary price: if oil is used as a source of energy, when the energy cost of recovering it exceeds its energy content, production will cease no matter what the monetary price may be.”

LLNL’s 2017 energy flowchart (below) indicates that amount of fossil fuel consumed by the USA’s non nuclear thermal power plants (22.45 quads worth \([9.54+12.7+0.21]\)), is about 85% of that consumed by its transportation system \(~100\%\) of which is petroleum-based. The efficiency with which its electrical power plants convert their fuels’ heat energy to electricity is about 40% while its transportation system is only about 21% \([5.91/28.10]\) efficient. Consequently, ignoring other losses
Figure 8: LLNL’s 2017 US energy Sanky diagram

replacing the USA’s fossil fuel powered transportation system with one powered with electricity generated by 40% efficient thermal-to-electric nuclear power plants would require \(7.76 \times 5.91^{*}21/40/0.4\) quads of such heat. That’s almost exactly that currently generated by its ~100 reactor LWR fleet (8.42 heat-type quads). At 3.2E-11J/fission, doing this would require the fissioning of 96 tonnes of uranium per annum (a 5.5 ft. cube if metallic) which would generate 96 tonnes of fission product radwaste.

3.2.2 Direct electrical transportation

Electricity represents an almost ideal future transport fuel (Gilbert and Perl 2010) – lightweight electrified vehicles for local passenger and
freight moving and high speed trains for almost everything else\textsuperscript{34}. Unlike other alternative transport energy scenarios, only electric mobility can move people and goods using any combination of raw energy sources—hydroelectric, wind turbines, and photovoltaic panels or gas turbines powered with coal, natural gas, oil, wood waste, solar energy, bio oil or, preferably, nuclear fission. Energy-wise, the majority of these vehicles would be grid-connected (GCVs) meaning that their electricity is generated remotely and delivered directly by wire or rail to its motor(s). GCVs currently do the majority of electrified people/freight moving. Electric streetcars and trains were operating in many cities by the end of the nineteenth century and \textasciitilde{}150 cities around the world have or are developing electric heavy-rail (e.g., metro and commuter rail) systems running at either the surface, elevated, or underground. Some 550 cities in Europe and Asia have streetcar and/or light-rail systems and about 350 have trolley buses. Electrification of intercity railroads began early in the twentieth century, although most of it occurred after 1950. Now most rail routes in Japan and Europe are electrified. Russia has the most extensive system; approximately half of its 85,000 kilometer total, including the whole of the 9,258-kilometer Trans-Siberian Railway is electrified. China’s rail system is being rapidly electrified and now boasts the world’s second-most extensively electrified transport system: 49 lines totaling about 24,000 kilometers. In these countries and elsewhere, those are mostly main routes and thus carry a disproportionately large share of their county’s passengers and freight. The revolution caused by introducing high-speed electrified passenger rail has transformed the way that people move between major applications.

\textsuperscript{34} see APPENDIX XIX
cities in Japan and Western Europe. Their primary advantage relative to battery-electric vehicles (BEVs) is lower cost and greater efficiency. No matter how good any powerful/long range BEV might become, it would still have to carry around a huge load of very expensive batteries which will take up space and increase its energy consumption. For example, an 85 kWh, “TESLA 3” car battery weighing 478 kg costs about $12,000 and stores as much primary energy as does about 2 gallons of diesel fuel. AGCVs would either need no batteries or only relatively small ones for limited “off-wire” travel. A GCV is subject only to energy distribution losses in moving the electricity from its source to the motor. For a BEV, losses incurred during the charging and discharging of its battery would likely be several times that distribution loss.

Nevertheless, there would definitely be a strong demand for small lightweight BEVs suitable for short range commuting, grocery shopping, etc. They should be designed around a government-standardized 10-20 kWh battery which could quickly switched-out at “filling stations” as envisioned by Thomas Edison over a century ago.

Other types of GCVs have been and continue to be used to move goods. These vehicles include diesel trucks with trolley assist such as were used in the Quebec Cartier iron ore mine from 1970 until that mine was worked out in 1977. These trucks were in effect hybrid vehicles with electric motors powered from overhead wires providing additional traction when heavy loads were carried up steep slopes. A diesel generator provided their electricity. The result was an 87 percent decrease in total diesel fuel consumption and a 23 percent increase in productivity.

Several direct comparisons of raw/primary energy consumption by GCVs with similarly capable vehicles with diesel-engine drives confirmed that energy use at the vehicle is invariably lower. For
example, in 2008 San Francisco electric trolleybuses used an average of 0.72 megajoule of energy per passenger-kilometer; in contrast, the average for diesel buses in the same city was 2.67 megajoules per passenger-kilometer.

If the electricity powering trolleybuses were to be produced by a diesel generator operating at 35 percent efficiency, with 10 percent distribution loss, the buses would still use less energy overall than do conventional direct diesel-powered buses. When electricity is produced renewably (e.g., by my thought experiment’s sustainable nuclear fuel cycle) the only thing that would count is such vehicles’ energy demand.

3.2.3 Nuclear transportation fuel synthesis

Though substitute transport fuel production such as coal or gas to-liquids, will likely increase over the next several decades, it’s unlikely to compensate for the decline of oil production and certainly would not address the environmental impacts of fossil fuel burning. Today’s alternative energy sources are not replacements for today’s oil. They (wind, solar, geothermal, etc.) produce electricity — not liquid fuels.

Another reason for “biocharing” the future’s nuclear-enhanced agricultural residues would be that doing so should simultaneously produce more than enough carbon-neutral “oil” to fuel the machinery required to run the farms and thereby become a profitable side line for their owners. Figures in a recent report about Nebraska’s farm fuel costs suggest that high-input corn farming currently requires about 70 US gallons of diesel fuel/ha/a (Agecon 2015). Five tonnes of bio oil purportedly has the energy content of ~37% that much No. 2 diesel oil (i.e., 2176 liters, 575 US gallons, or 82 GJ’s worth) and it should be possible to convert it to a good diesel-type engine fuel (Cataluna 2013). Consequently, such farms would generate about seven times as much motor fuel as they consume.
A host of other transport fuel-related possibilities are raised by the fact that a properly implemented nuclear renaissance would render electrolytic hydrogen much cheaper than it is now. For instance, hydrogenation of the \( \sim 11.6 \, \text{t/ha} \) of stover that I’ve mentioned above would produce about 3x as much synthetic fuel oil (\( \sim 4.9 \times 10^8 \, \text{tonnes/a} \)) as would making it from biocharing’s bio oil intermediate (Agrawal 2007). Such fuel would also be carbon-neutral because it was derived from plant matter that had received its carbon from the atmosphere.

Similarly, if Africa’s 4.5 billion future citizens were to produce/consume as much Portland-type cement per capita as we do now, Fisher Tropsch hydrogenation of the \( \text{CO}_2 \) so generated would produce about \( 8.2 \times 10^8 \, \text{Mg} \) (metric tonnes) of transportation fuel/a, which figure divided by 4.5 billion represents \( \sim 28\% \) of current world per capita petroleum consumption rate. Unfortunately, even if that cement were to be made with nuclear powered kilns, such fuel would not be carbon neutral because limestone would still have to be calcined.

Another possibility that would not dump such carbon into the atmosphere would be to make additional “nuclear ammonia” and use it to fuel engines and/or fuel cells (Kanga and Holbrook 2015). For example, the shipping industry is beginning to evaluate ammonia as a potential carbon-free alternative to the heavy fuel oil (“bunker fuel”) used in maritime transport.

Putting proposals like these into proper perspective, requires more ball park calculating.

According to the EIA, of the 7.3 billion barrels of petroleum consumed by the USA during 2017, 47% was motor gasoline, 20% was distillate fuel (heating oil and diesel), and 8% was aviation fuel – other words about 75% of petroleum is used to fuel some sort of engine. That year,
the entire world consumed about 83 million barrels of it per day or 30.3 billion barrels total. Oil’s raw combustion heat energy is about 6.1 GJ/barrel (159 liters or 42 US gallons) which translates to about 42 GJ/tonne: liquid ammonia’s combustion heat is 383 kJ/gram mole (17 grams) which translates to 22.5 GJ/tonne and making it via electrolytically generated H₂ requires about 14.2 MWh of electrical energy.

75% of 30.3 billion barrels of oil consumed by 35% heat-efficient engines adds up to 4.85E+19 (0.75*30.3 E+9*6.1E9) Joules worth of energy services (useful work). Providing that much useful energy via “direct electricity” would require the full time output of 1538 [4.85E+19/1E+9/3.15E+7] one GW_e reactors.

If we assume that those energy services were to be provided by engines burning “nuclear ammonia”, 6.19 billion [= 0.75*30.3E+9*6.1E9/22.5E+10] tonnes of it would be needed per year. At 14.2 MWh/tonne, making that much of it with electricity would require the full-time output of 9970 [6.19E+9/14.2*3.E+9/1E+9/3.15E+7] one GWe nuclear reactors – over six times as many.

The lesson that ball park calculations like these should teach us is that our descendants should electrify as much of their world’s transport system (and almost everything else) as possible.

The shipping industry currently emits about 1 gigaton of CO₂ per year, or 2.33% of global emissions, according to Low Carbon Pathways 2050, a “$4 million multi-university and cross industry research project. International trade associations are leading the effort to decarbonize that economic sector in alignment with the goals set by the Paris Climate Agreement. Their immediate challenge is simple to state but hard to
address: “ambitious CO₂ reduction objectives will only be achievable with alternative marine fuels which do not yet exist.”

To meet the targets defined by the Paris Agreement, the study determines that the shipping industry would need to achieve “net zero emissions by approximately 2035 (1.5°C) and 2070 (2°C).”

Its key findings conclude that the industry needs to do two things: first, act swiftly and, second, identify a viable carbon-free liquid fuel (Lloyds 2016).

• Shipping will need to start decarbonisation soon because as stringency increases over time, increasingly costly mitigation will be required. The later we leave decarbonisation, the more rapid and potentially disruptive it will be for everyone.

• A substitute for fossil fuel will still be required as energy efficiency improvements alone will not be sufficient in the medium to long term.

• Energy storage in batteries and politically correct renewable energy sources will have some role to play, but will likely to still leave a requirement for a liquid fuel source.

While low carbon fuels (bio or synthetic fuels such as ammonia) may be necessary in the timescales modeled in its report to enable international shipping’s low carbon transition, under current technology costs they were not deemed economically viable (UMAS 2017).

Another recent CISRO study concluded that, “Liquid hydrogen and methanol, despite also being alternative energy vectors, have lower round trip energy efficiencies [than ammonia] as estimated in previous studies. Further, the infrastructure required for liquid hydrogen transport is almost nonexistent and methanol is an emission producing fuel at the point of use; make these alternatives less attractive at this
stage. Ammonia therefore provides an attractive option in terms of RTE, as well as being an emission-less energy carrier” (Giddey 2017).

However, most of these studies assumed that ammonia would only be used in the currently expensive “ammonia fuel cells”, overlooking its potential in combustion-based engines.

The first such use that I’m aware of occurred at the same Norwegian hydropower plant that produced the heavy water (D$_2$O) which was to be the moderator$^{35}$ of Germany’s first nuclear reactor during WW II$^{36}$. Before that war most of its electricity had been used to make fertilizer ammonia with electrolytically-generated hydrogen. A bit of that ammonia fueled the truck depicted in Figure 9. Germany’s war time

$^{35}$ A moderator’s purpose is to slow down the extremely fast (high energy- 1-2 Mev) neutrons created during fission and thereby increase their probability of capture by other fissile atoms. The world’s first nuclear reactors had to be moderated because they had to be fueled with natural, not “enriched”, uranium. This means that their fuel’s $^{238}$U atoms out-numbered their fissile $^{235}$U atoms 140:1 (1/0.0071). That’s important because of $^{238}$U’s tendency to irreversibly absorb neutrons moving at speeds intermediate between what they possessed when first released and after slowing down to speeds corresponding to a gas at room temperature (i.e., its “resonance absorption region”). If small chunks of uranium are surrounded with the right amount of a suitable moderator, enough neutrons can get through $^{238}$U’s “resonance absorption gauntlet to trigger fission of the next $^{235}$U atoms that they blunder into and thereby keep a chain reaction going. A perfect moderator atom does not “capture” (irreversibly absorb) neutrons, it’s just something that they can repeatedly collide with and thereby loose kinetic energy. All else being equal, the lighter the atom, the better it serves that purpose. While hydrogen is actually a better moderator than deuterium, it absorbs too many neutrons to permit a reactor containing natural uranium (0.7% fissile $^{235}$U) to reach criticality because it also irreversibly absorbs too many neutrons.. That’s why a light water-moderated reactor’s uranium must be “enriched”.

$^{36}$ Since electrolytic hydrogen gas is somewhat richer in the light isotope (H) than is the liquid water from which it is made, repeated distillations can produce the pure heavy water (D$_2$O) required to moderate natural uranium-fueled reactors. That’s why Hitler’s Germany demanded that it become Norsk Hydro’s raison d’etre.
scientists never did get their reactor built but the Norwegians continued to power their truck and fertilize their fields with ammonia.

If France’s leadership 30–40 years ago had decided to build enough additional reactors to produce its own synfuels as well as electricity, its current “yellow vest” populist uprising would not be happening.

![Norsk Hydro’s ammonia-fueled truck circa 1933](image)

**Figure 9: Norsk Hydro’s ammonia-fueled truck circa 1933**

There are several technical challenges that an ammonia-fueled engine must overcome. The Caterpillar Corporation put it succinctly in their 2008 patent application covering a “power system having an ammonia-fueled engine”: “When ammonia is combusted, the combustion produces a flame with a relatively low propagation speed. Its low combustion rate causes it to be inconsistent under low engine load and/or high engine speed operating conditions. Most existing combustion engines that use ammonia as fuel require a combustion promoter (i.e., a second fuel such as gasoline, hydrogen, diesel, etc.) for ignition, operation at low engine loads and/or high engine speed.”

In other words, one option is to use a liquid combustion promoter. However, as Caterpillar’s patent subsequently noted, this approach “generally requires dual fuel storage systems, dual delivery systems, and dual injection systems, thus adding additional weight, complexity, and cost to the engine system.”
The second option is to use hydrogen as the combustion promoter. A promising variant of this approach is to place an on-board “reformer” between the fuel tank and the engine. The reformer “cracks” enough of the ammonia into hydrogen and nitrogen to ensure reliable combustion. Crackers can be simple in mechanical terms, consisting of a heated chamber furnished internally with a catalyst. However, the patent describes one more challenge: “The requirement for the combustion promoter fuel fluctuates with varying engine loads and engine speed, which can cause control issues.” This means that cracking a fixed proportion of the ammonia (or a proportion that varies simply with the rate of fuel flow) is unlikely to produce good engine function.

A third option would be to use it as Honda currently does with the optimally operated, very small,\(^\text{37}\) gasoline engines charging the batteries of its hybrid cars. This makes especially good sense in areas that get too cold for “pure” BEVs to function properly (e.g., most of Canada).

There are many ammonia engines in development, including by Caterpillar, a major supplier of maritime, tractor, truck, and industrial engines. In addition, some major industrial projects will soon demonstrate the environmental benefits of ammonia in dual-fuel combustion. If the shipping industry is committed to acting quickly and identifying carbon-free liquid fuels (“which do not yet exist,” they say),

\(^{37}\) They can be small because car engines have to provide only 7 to 15 KW (10-20 horsepower) most of the time. A reasonable-size, e.g., 5 kWh, lithium ion or lithium hydride battery can provide far more power than that for short bursts. This also means that a relatively small (perhaps 15-20 kW ) direct ammonia fuel cell coupled with a roughly 3-5 kWh battery could power our descendant’s automobiles with roughly twice that overall efficiency (see Zhao 2019)
it must evaluate ammonia as a short-term bridge fuel for engines, as well as a long-term energy source for fuel cells.

Ammonia is emerging as an economically viable fuel for dual fuel engines where it is substituted for natural gas (Technavio 2016). When ammonia is so used, a significant reduction in CO₂, PM (particulate matter) and rather surprisingly even NOx, emission levels is observed. Ammonia is a high-octane fuel (possesses a high resistance to pre-ignition), which means that higher compression, more efficient, engines can be used. Consequently properly modified ammonia-fueled engines exhibit enhanced power output compared to their gasoline or diesel fueled counterparts.

Technavio noted that shipping represents roughly 65% of the market for dual fuel engines, which are “gaining popularity in the marine industry as a growing number of vessels are using these engines over conventional diesel or gas engines ... enabling the crew to adhere to various marine pollution (MARPOL) regulations regarding propulsion engine emissions.”

Farm tractors represent another big potential market for such engines because they typically run at “full load”, and, due to ammonia’s popularity as a fertilizer, much of the necessary fuel distribution infrastructure already exists.

3.3 “The Age of Substitutability”

Table 4: The USA’s material needs circa 2009

__________________________

38 Gaseous ammonia injected directly into moist soils is immediately hydrolyzed to ammonium ion which is strongly retained by the soil’s cation exchange capacity.
Table 3 lists major US raw materials consumption other than water and sand/gravel circa 2009. Note the dominance of fossil fuels. Goeller and Weinberg’s “The Age of Substitutability” approached the problems posed by the future’s otherwise inevitable “cheap” raw resource depletion with empirical technical data rather than the then and still dominant economic models. Their paper went through the entire periodic table examining all the elements plus some of their more important compounds, to determine humanity’s demand for them circa

\[ \text{Mtonnes/a (Imported)} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Mtonnes/a (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum</td>
<td>3.25 (45%)</td>
</tr>
<tr>
<td>ammonia</td>
<td>22 (45%)</td>
</tr>
<tr>
<td>plastics</td>
<td>28 (?)</td>
</tr>
<tr>
<td>steel</td>
<td>93 (25%)</td>
</tr>
<tr>
<td>cement</td>
<td>100 (20%)</td>
</tr>
<tr>
<td>natural gas</td>
<td>403 (19%)</td>
</tr>
<tr>
<td>coal</td>
<td>858 (2%)</td>
</tr>
<tr>
<td>oil</td>
<td>984 (71%)</td>
</tr>
<tr>
<td>( \Sigma \text{fuels/total materials} )</td>
<td>90.12%</td>
</tr>
</tbody>
</table>

\(^{39}\) For instance, the fully oxidized carbon within carbonate rock can’t be used for the same things as can the carbon within fossil fuels.
1970, estimating for each the total resource available assuming a broad definition of potential sources – the atmosphere, the ocean and the uppermost one mile-thick layer of the earth’s crust – not just “rich” ores. The ratio of total resource to demand was determined for each element in terms of years until exhaustion – a measure of their relative abundance or scarcity. Throughout that list, in cases where there was a clear indication of a finite life time, they identified that element’s most important uses and possible substitutes. For example, some combination of abundant titanium, aluminum, and iron could probably serve the same purposes currently served by much rarer metallic elements. Aluminum could be obtained from abundant clays rather than rare bauxite and titanium substituted for exotic stainless steels. Based upon their analysis of geological and technological data, they then pronounced the principle of “infinite substitutability”; i.e., with the exception of phosphorus, mercury, and most importantly, the chemically reduced forms of carbon and hydrogen (coal, oil and gas) serving both then and now as fuel, a rich modern civilization could continue indefinitely utilizing only the Earth’s nearly inexhaustible resources. The key to such a future would be the availability of energy cheap enough to wrest valuable materials from low grade ores rather than from much less abundant rich ones.

Another reasonable substitution that Goellor and Weinberg didn’t mention would be to switch from Portland to geopolymeric-type cements (Hardjito 2005). Concrete is currently the world’s fourth-most human-consumed substance after water, sand/aggregate, and fossil fuels.

40 One of the reasons that the “dry” phosphate process has largely been supplanted by a sulfuric acid leaching-based process is that it requires more electricity. Electricity used to be cheaper in places like Idaho because its rapidly increasing population’s power demand now exceeds its aging hydroelectric plants’ capacity to generate cheap electricity.
An average of approximately three tons of it is produced for every person on earth each year. Making the Portland-type cement “binder” utilized in the majority of it accounts for ~5% of current anthropogenic CO$_2$ emissions, one-half of which is due to the fossil fuels (mostly coal) currently heating most cement kilns.

Since about 3 GJ of heat energy is required to make one ton of Portland cement (Hewlett 2012), the ~3.7E+9 tonnes of it currently produced/consumed each year would require ~1.12E+19 J of electricity – equivalent to the full time output of about 355 full-sized nuclear reactors (~1.2% of the total (~30,000) needed to satisfy 100% of our descendants’ energy needs).

The substitution of geopolymeric binders (cements) – mixtures of low calcium fly ash and/or calcined clay “activated” by solutions containing ~15 wt% Na$_2$O in the form of sodium silicate and 45 wt% NaOH – for Portland-type cements would greatly reduce carbon emissions. Even if the sodium hydroxide utilized to make the activators were to be produced by reacting lime (CaO) with sodium carbonate (trona), only about 15% as much limestone would have to be calcined to produce an equivalent amount of finished concrete.

Another plus for geopolymeric concretes is that they are more durable than are those made with Portland cement or “Roman” (lime-pozzolana) cementitious binders. The reason for this is that the sand/aggregate binding-mineral assemblage formed during their curing process is neither hydrated nor readily carbonated by atmospheric CO$_2$ and/or bicarbonate-containing water.

A third alternative to conventional Portland cement would be granulated “dry process phosphate slag”. That process (Swann 1922) utilizes an electrically blown/heatened “blast furnace” to convert a mix of powdered
phosphate rock ore, iron ore, and coke into gaseous elemental phosphorous, liquid ferrophosphorus (a valuable by product), and a molten glass-like calcium silicate slag. That process’ “waste” slag is essentially the same thing as iron blast furnace slag which means that if it were to be treated correctly - rapidly cooled, powdered, and mixed with an activator (e.g., lime or sodium silicate) - could serve the same purposes as does ordinary Portland cement (Criado 2017). It couldn’t totally supplant the latter because the world’s current demand for phosphate rock (~250 million tonnes) is under 10% of its demand for Portland cement (~4 billion tonnes).

Finally, regardless of which sort of sand/aggregate binder is employed, the future’s concrete infrastructure would last much longer if basalt fiber reinforcing bar/wire were to replace today’s steel rebar (Basalt rebar 2016). Modern lightweight steel rebar-reinforced concrete structures are less durable over the long haul than were those made by the Romans because the carbonation of any calcium silicate based concrete eventually lowers the pH of its pore fluids to a point that allows embedded steel rebar to rust, expand, and thereby crack the concrete surrounding it. Basalt fiber rebar does not rust and is intrinsically cheaper than steel rebar because the majority of the earth’s crust consists of basalt and melting/spinning it requires less energy than does iron smelting. It is also ~7 times stronger mass-wise than steel, which means that less of it would be required.

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40 One of the reasons that the “dry” phosphate process has largely been supplanted by a sulfuric acid leaching-based process is that it requires more electricity. Electricity used to be cheaper in places like Idaho because its rapidly increasing population’s power demand now exceeds its aging hydroelectric plants’ capacity to generate cheap electricity.
The energy generated by ~75 one GWe reactors could produce 1.5 tonne/year of environmentally correct, basalt fiber reinforced, geopolymeric concrete for eleven billion people each year.

Of course those substitutions would be impossible unless some sort of abundant, reliable, cheap, and clean power/energy source replaces today’s finite carbon-based industrial fuels. Of the possibilities consistent with Mother Nature’s rules and facts, Goeller and Weinberg concluded that breeder-type nuclear reactors offered the most promise. Unlike the majority of the world’s political leaders both then and now, they recognized that over the long haul, decisions based upon technical information (facts) will serve humanity better than those based upon convenient political and econometric assumptions (alternative facts).

“Anyone who believes in indefinite growth in anything physical, on a physically finite planet, is either mad or an economist.”

Kenneth Boulding

3.4 Still more apps

If the world were to be fully electrified via a properly implemented nuclear renaissance, its air and water would be cleaner, its homes and cities more livable, and far more interesting, better paying, and more secure employment opportunities would be available to its young people because they would be the ones employed building/maintaining their brave new world. Finally, a rarely mentioned (too politically incorrect) reason for China’s monumental success during the last four decades is that its leadership adopted/enforced a one child per family policy at the same time they decided to encourage/enable its people to
become both creative and entrepreneurial (Conly 2015). The purpose of that policy was to free up time and capital which could then be (and was) devoted to “making China great again”. It also rendered children born during that period especially “special” to both their parents and society-at-large which in turn rendered their lives more enjoyable and successful. Population growth rate would drop precipitously (CATO 2013) as would the degree of misery/desperation/frustration currently driving young people everywhere (mostly males) to join terrorist gangs and hate groups. In other words, the world’s currently desperately poor people would experience the same benefits of nuclear powered prosperity that Japan’s, South Korea’s and China’s have enjoyed.

A government’s job is not just to give its currently most important citizens (its leader’s “base”) whatever they want, but to pave the way for a prosperous, stable, and safe future for everyone. Any kind of government mandated fertility control is unattractive, but unless its goals are achieved otherwise (e.g., by improving the lives and futures of already-living people), it’s apt to become necessary everywhere if wars don’t render that subject moot.

Chapter 4. Why sustainability requires breeder reactors

Light water cooled/moderated reactors (LWRs) generate the vast majority of the world’s nuclear power – it’s become a locked in technology (Cowan 1990).
Figure 10: Power reactor types, IAEA 1987

There are two basic types of LWRs (Figure 10): Pressurized Water Reactors (PWRs) in which the normal (i.e., H\textsubscript{2}O aka “light”) water surrounding/cooling their fuel rods within the core isn’t allowed to boil, and Boiling Water Reactors (BWRs) in which it is.

Figure 11: State of the art Gen III\textsuperscript{+} PWR schematic
They are otherwise similar in that: 1) their fuel rods consist of zirconium alloy tubes containing enriched (typically 3 to 5% $^{235}$U) uranium oxide pellets; 2), they operate at very high pressures (>1000 psi) but low temperatures (~285°C); and 3), they “waste” many of the neutrons generated when the fissile atoms fueling them (mostly $^{235}$U) “split”. The latter characteristic refers to the fact that in moderated reactors, too many neutrons are “captured” by materials (water, zirconium, fission products, control rods, and “burnable poisons”) other than the fertile $^{238}$U comprising the bulk of the uranium, meaning that they can’t “breed” as much fissile (in this case, $^{239}$Pu) as they consume. Consequently, regardless of how small and modular they might become, any “advanced” version of today’s light water cooled/moderated reactors (e.g., NUSCALE’s 60MWe SMR) would consume at least ~160 tonnes of natural U/GW/year, most of which, primarily $^{238}$U, would be discarded during its fuel fabrication’s U-enrichment step. A genuinely sustainable nuclear renaissance could not be implemented with them or any other sort of burner/converter-type

41 “Small” and “modular” are about the only “advanced” reactor characteristics that DOE NE’s leaders have consistently emphasized/supported for the last 15 years or so. That's why we've ended up with inefficient mini-LWRs (NUSCALEs) instead of something able to “save the world”. "Modular" and "small" are fine attributes if seeking them doesn't distract research scientists/engineers from concentrating upon what they should be trying to accomplish. A downside of "small" is that there's about as much overhead cost associated with running a small power reactor as there is a big one. Another is that neutron leakage is higher/GW, meaning that they don't “breed” replacement fissile as well. If the world is to be powered with fission-type reactors, they must be able to at least isobreed. "Modular" is desirable any way you look at it and many powerful molten salt reactor concepts could be modular because their cores would be small.

42 Although most of the natural uranium (NU) discovered/mined/processed to make LWR fuel never ends up in that fuel, all of it must be converted to uranium hexafluoride – the gaseous form required by the world’s isotopic separation (enrichment) facilities.
reactor because the uranium industry's official estimate of all affordable (in that context) “proven plus undiscovered uranium resources” is only ~18 million tonnes (Redbook 2014). Generating 2 kW’s worth of LWR-generated electrical energy for 11.2 billion people, would consume 100% of the world’s “affordable” uranium within about 5 years [1.8E+7/22,000/160 = 5.1].

People championing such a burner/converter reactor-implemented nuclear renaissance do so based upon economic models & wishful thinking rather than geological/technical data; i.e., they assure us that sufficiently cheap uranium will inevitably be discovered when the definition of “affordability” rises beyond today’s upper limit, <$260/ kg. For example, if a ten-fold price increase would indeed unearth 300 times as much uranium (Deffeyes & McGregor 1980)\(^4\), a conventional light water reactor -based, 22 TWe, nuclear renaissance could be fueled for several centuries before the cost of its resource-fuel (i.e., natural uranium – NU) exceeded that of coal-fired power plants if the price of coal were to stay the same as it is now. Unfortunately, I see no proof that Mother Nature actually follows any such relationship, which, in turn, renders such assurances unconvincing (see Höök &Tang 2013). For example, the uranium industry’s latest (2018) Redbook's fuel resource figures do not support Deffeyes & McGregor’s rule-of-thumb; i.e., that a tenfold increase in what we’re willing to pay for uranium would generate 300 times as much of it. Plots of that Redbook’s \(\log_{10}(\text{resource size})\) vs \(\log_{10}(\text{cost})\) data possess slopes of from 1.10 to

\(^4\) Kenneth Deffeyes was a geologist who worked with M. King Hubbert at the Shell Oil Company’s research laboratory and then became a Princeton University professor. He authored the book, Beyond Oil: The View from Hubbert's Peak.
1.25 depending upon whether the resource in question is “identified”, “reasonably assured”, or “inferred”. Their rule of thumb implies a slope of 2.477 \([\log_{10} 300/\log_{10} 10]\).

**Table 5:** Average uranium concentrations (parts per million) in ores, rocks and waters (Ulmer-Scholle 2018).

<table>
<thead>
<tr>
<th>Material</th>
<th>Concentration (ppm U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-grade orebody (&gt;2% U)</td>
<td>&gt;20,000</td>
</tr>
<tr>
<td>Low-grade orebody (0.1% U)</td>
<td>1,000</td>
</tr>
<tr>
<td>Average granite</td>
<td>4</td>
</tr>
<tr>
<td>Average volcanic rock</td>
<td>20 – 200</td>
</tr>
<tr>
<td>Average sedimentary rock</td>
<td>2</td>
</tr>
<tr>
<td>Average black shale</td>
<td>50 – 250</td>
</tr>
<tr>
<td>Average earth's crust</td>
<td>2.8</td>
</tr>
<tr>
<td>Seawater</td>
<td>0.003</td>
</tr>
<tr>
<td>Groundwater</td>
<td>&gt;0.001 – 8</td>
</tr>
</tbody>
</table>

The notion that we simply haven’t yet bothered to look hard enough for uranium (or thorium) is also questionable because unlike most of the mineral resources that mankind seeks, natural actinides are always accompanied with sufficient mildly radioactive decay products to be easily detected with readily available, cheap, portable, meters.
The Earth’s total surface area is about 510 million square km, ~29% of which is land. Assuming a rock density of 2.8 g/cc the mass of land-sited crustal rock to a depth of 1 km is about 4.14E+17 tonnes. Since such rock contains an average of 2.8 ppm uranium, the total mass of “accessible” uranium (we’re already digging deeper than that for oil, gas, gold, and diamonds) in it comes to about 1.16E+12 metric tonnes or 64,000 times that currently deemed “affordable” if utilized by today’s inefficient burner/converter reactor-based nuclear fuel cycle.

The real problem is that the vast majority of the world’s uranium is in low grade (~100 ppm) deposits (shales, phosphate rock, etc.) too expensive to mine and then process to feed a grossly inefficient nuclear fuel cycle.

Another commonly made/heard assertion, that the “reprocessing” of today’s ~240,000 metric ton (total actinide) accumulation of spent LWR fuel could address their fuel limitation issues is also wrong. It takes about six spent LWR fuel assemblies to make one “MOX” fuel assembly and that process can only be done once because such fuel’s “reactor grade plutonium” is degraded to “crap grade” plutonium that cannot be further burned in the same sort of reactor. This means that the maximum possible such fuel supply extension would be about 17%. MOX fuel is also expensive to make and relatively dangerous/bothersome to use, which is why most independent reviewers and all US electrical utilities have concluded that it’s not worth the trouble.

For instance, a 2007 analysis of the pros and cons of reprocessing concluded that a US built reprocessing plant would cost about $50

44 Appendix I describes the hows and whys of reprocessing.
billion and its operating cost would be $1000–3000 per kg of spent fuel processed (Bollgren 2007).

Ignoring build costs and assuming $2000/kg spent fuel processing cost, making 1 kg of fuel for a reactor-grade plutonium-based, MOX fuel would cost about $12,000 (6*2000). Assuming 4.5% enrichment and 0.0015 tails (\(^{235}\)U) discard (21%), making one kg of NU-based fuel would require ~8 kg of NU \([.045/(.0071-.0015)]\). The current cost of NU is about $62/kg which makes the U going into in a kg of such fuel worth about $372. Doubling that figure to account for its enrichment cost, one kilogram of that fuel’s initial “heavy metal” (actinides) comes to $744 or just 6.2% that of MOx-based fuel.

The reprocessing of spent light water reactor fuel makes economic sense only if the actinides so recovered serve to fuel breeder-type reactors\(^{45}\).

Because any genuinely sustainable nuclear fuel cycle would require the resumption of reprocessing in one form or another, I’ve written APPENDICES I & II to describe its history and what its future might look like.

Fueling burner/converter-type reactors with uranium extracted from seawater couldn’t “save the world” either. The country most involved with testing/developing that scenario is Japan (see Tamada 2009 for a slide set and lecture). Dr. Tamada’s slides begin with the contention usually prefacing such reports; i.e., that “there's 1000x as much U in the oceans as on land”. That’s incorrect because there's about 350 times as

\(^{45}\) However, even at $12,000/kg such fuel costs only about one half as much per kWh as does typical US coal.
much U in “readily accessible” rock (the first kilometer of the ~3 ppm U crustal rock covering the earth’s land surfaces) as in its seawater (~1.33 billion km$^3$ of ~3 ppb U water). Dr. Tamada’s slides then go on to describe Japan’s pilot plant scale demonstrations and end with a conclusion that a 68.7 by 15.2 km (1030 km$^2$) array of the most promising uranium adsorbent developed (amidioxime-coated, irradiated polyethylene fiber “ropes”) might be able to collect enough uranium to fuel six of Japan’s almost state-of-the-art LWRs (i.e., ~1200 tonnes U/a) for a “reasonable” cost. That conclusion assumed that the adsorbent would be trapping ~4 g U/kg adsorbent per cycle, roughly three times more than was generally recovered during their demonstrations (Regalbuto 2014). A subsequent US study concluded that an “improved” version of that adsorbent would capture ~3.3 g U/kg adsorbent (Kim et al, 2014). In any case, because those adsorbent arrays must be bottom-anchored, experience significant wave action, and situated where natural currents quickly replenishes the water surrounding them, almost 4 million km$^2$ of shallow (mostly coastal) ocean bottom would have to be covered to fuel 22 TW’s worth of conventional burner/converter-type reactors. Finally, anyone considering such schemes should be aware that both fishermen and the world’s “Rainbow Warriors” are apt to object – the former because their nets and lines would surely become entangled by so-situated gigantic synthetic “kelp beds“, the latter because those arrays might also entangle/strangle seals, whales, and turtles.

Other than for those little technical details, mining the oceans to fuel conventional burner/converter-type reactors is a really fine idea.
On the other hand, coupling Dr. Tamada’s uranium filters to a breeder reactor powered desalination plant’s brine outlet could collect about 20 times as much uranium as that reactor would consume. This means that if the energy devoted to the future’s water desalination systems represents >5% of mankind’s total needs, seawater could indeed fuel everything.

Realization of Weinberg and Goeller’s utopian (but possible) future can happen only if the future’s decision makers decide to first develop and then implement an appropriately scaled (big enough), sustainable, nuclear renaissance and then see to it that untrammeled human nature does not turn that/their project into yet another interminable cost-plus nuclear boondoggle.

A genuinely sustainable nuclear fuel cycle must be implemented with reactors that generate (“breed”) as least as much new fuel (“fissile”, any readily fissioned actinide isotope) as they consume from “fertile” natural uranium and/or thorium and thereby constitute a “renewable” power source. A non-renewable resource (aka finite resource) is a resource of economic value that cannot be readily replaced by natural means quickly enough to keep up with consumption. Fossil fuel generated power/energy is non-renewable because Mother Nature’s fuel-making reactions are many orders of magnitude slower than is the rate at which we are consuming them.

\[46\text{ Assuming that the desalination plant processes twice as much seawater as it produces fresh water and that its breeder-type power plant’s heat to electricity conversion efficiency is 50%, it would take about 3\text{kWh’s of fission heat to process each cubic meter of seawater.} \text{3\text{kWh} = 1.05E+7 Joules requiring 3.28E+17 U atoms which =’s 1.3E-4 grams }^{238}\text{U. One m}^3\text{ of 3 ppb seawater contains 3E-3 grams of U – about 23 times more than that reactor would “burn”.
}]}
For example, each year the Earth's plant life "fixes" about 7.8×10\(^{13}\) kg of atmospheric carbon of which \(~99.9\%\) is oxidized back to CO\(_2\) and returned to the atmosphere when those plants die (Ableson 1975). The majority of the 0.1% that isn't so oxidized mixes with the clay fraction of soils to form organic ("black") shales where it is very gradually converted it to some combination of humic acids, kerogens, peat, graphite, coal, natural gas, and petroleum. 99.5% of the roughly 2% of it that eventually ends up as petroleum remains tightly bound within those shales. Consequently, Nature's overall petroleum-type fuel carbon production rate is about 1.56×10\(^9\) (7.8×10\(^{13}\)×0.001×0.02) kg/year of which 7.8×10\(^6\) kg is as easily/cheaply recoverable as was Saudia Arabia’s petroleum 50 years ago. Mankind currently consumes (mostly by burning to CO\(_2\) plus water vapor) about 93 million barrels of petroleum per day which translates to about 3.7×10\(^{12}\) kg of carbon (=’s 13.6×10\(^{12}\) kg CO\(_2\)) per year which mostly ends up in the atmosphere: in other words, we're burning petroleum \(~475,000\) times faster than Mother Nature is creating it.

"It is hard to know which is the more remarkable - that it took 600 million years for the Earth to make its oil, or that it took 300 years to use it up."

M. King Hubbert

Breeder reactors, not today’s power reactors, would be renewable because it would be easy/cheap to fuel them for at least as long as Homo Sapiens is apt to exist – hopefully (and I feel optimistically) another million years.

**Chapter 5. Today’s more promising breeder reactor concepts**
5.1 Heavy water thorium breeders

Probably the quickest way to begin the implementation of a suitably fuel efficient (sustainable) nuclear fuel cycle would be to convert today’s ~293 already-paid-for pressurized water reactors (PWRs) to breeders by replacing their uranium-based fuel assemblies with uranium/thorium based assemblies and substituting “heavy” water (D\textsubscript{2}O) for the “light” water (H\textsubscript{2}O) currently used to both moderate and cool them (Permana 2008). The reasons to expect much better (more fuel efficient) performance are that deuterium doesn’t consume (waste) nearly as many neutrons as does hydrogen, and \textsuperscript{232}Th can efficiently breed its fissile (\textsuperscript{233}U) with slow-moving (moderated) neutrons while \textsuperscript{238}U can’t. The same changes would probably also enable the World’s ~77 full scale “boiling water reactors” (BWRs) and 32 CANDU-type reactors to achieve breakeven fissile regeneration (Greenspan 2014, CANDU 2019).

Unfortunately, so-modified/operated reactors would possess the same weakness of today’s LWRs and High Temperature Gas (cooled) Reactors (HTGRs); i.e., in order to run for a fairly long time\textsuperscript{48}, their fresh fuel assemblies would have to contain extra fissile, meaning that its initial excess reactivity (which would otherwise cause run away heat generation - an “explosion”), would have to be suppressed with control

\textsuperscript{47} Fissile breeding (aka fuel conversion) plays a significant role in the fuel cycle of all commercial power reactors. During fuel burn up the fertile material (usually \textsuperscript{238}U) is converted to fissile \textsuperscript{239}Pu which partially replaces the “burned” fissile \textsuperscript{235}U, thus permitting the reactor to operate longer before the total amount of fissile in it decreases to the point that criticality is no longer achievable. The ratio of new fissile formed to that consumed is called “conversion factor” which is acronyed either CR or BR: If CR<1 the reactor is a converter (aka burner); if CR= 1, it’s an isobreeder; if CR>1, it’s a breeder.

\textsuperscript{48} A LWR’s ~1000 psi operational pressure renders it impossible to gradually add fissile.
rods and/or burnable “poisons” both of which deliberately absorb (waste) neutrons that could otherwise serve to breed fresh fissile. This translates to very little fuel burn up per cycle (~10 GWd/t), short refueling intervals, and lots of expensive/fussy solid fuel reprocessing and fuel assembly refabrication49.

“Burnup” is a measure of the amount of heat generated per tonne of the core’s total actinides (“heavy metals” or HM) per “burn” cycle. For example, let’s assume that a 33% heat-to-electricity efficient, 1 GWe PWR generates 25 tonnes of spent fuel per year of which 20 tonnes was initially uranium (mostly 238U enriched to about 5% 235U)

\[
\text{total heat generated per year} = \frac{1}{0.33} \times 1 \times 10^9 \text{ J/s} \times 3.15 \times 10^7 \text{ s/a} = 9.56 \times 10^{16} \text{ joules}
\]

1 GWd = 1 E+9 J/s * 3600 s/hr * 24 hr/day = 8.64 E+13 joules
"burnup" in the usual units = 9.56 E+16 / 8.84 E+13 / 20 = 55.3 GWd/tonne HM

HM consumed/year = 9.56 E+16 / 3.2 E-11 J/fission * 235 g/mole / 6.023 E23 atoms/mole / 1 E+6 grams/tonne = 1.17 tonnes

Fraction HM burned = 1.17 / 20 = 5.8%

100% burnup corresponds to ~949 GWd/t.

49 A year’s worth of fuel for a typical pressurized water reactor consists of about forty, 4 meter long, fuel assemblies each consisting of ~289 thin-walled Zircalloy tubes containing sintered/pelletized low enriched (typically 3-5% 235U) uranium oxide (Croft 2008). Their fabrication currently costs about twice as much as does the uranium going into them. Altogether, a typical power reactor’s fuel-related costs sum to ~ $0.008/kWh. Reprocessing such fuel involves chopping the tubes into short pieces; roll-crushing them to release the brittle uranium oxide ceramic pellets within them; dissolution of that ceramic in strong nitric acid; counter current liquid-liquid extraction of that solution with a solution of tributylphosphate (TBP) in kerosene to separate/recover the actinides: back extraction of those actinides into dilute nitric acid, adding a reducing agent (typ. ferrous ion or hydroxylamine) plus more strong nitric acid; and finally, reextracting the uranium back into more TBP/kerosene leaving the now trivalent plutonium (Pu+3) in the aqueous phase.
5.2 Liquid metal fast breeder reactors (LMFBRs)

Another solid fueled reactor concept has already been implemented and more or less thoroughly tested in the US, France, Japan, and Russia. Russia’s first LMFBR, the “BR-1”, was designed in 1949 and commissioned at Obninsk in 1955—four years after the USA’s tiny “EBR I” was fired up. After that, two more Russian reactors, the BR-5 and BOR-60, were commissioned & tested, both there and at the Research Institute of Atomic Reactors (RIAR) in Dimitrovgrad. These paved the way via an intermediate—sized (1000MWt, 125 MW\textsubscript{e} (most of its heat energy was used to desalinate Black Sea water) “BN 350”, to Beloyarsk’s first almost full-sized LMFBR, the BN-600, which has purportedly been generating 600 MW of electricity since 1980. Based upon that success, construction of the bigger BN-800 began in 1984. However, after the USSR’s genuinely disastrous and really stupid 1986 Chernobyl screw-up\textsuperscript{50}, and that union of socialist republic’s subsequent collapse\textsuperscript{51}, that reactor’s construction was suspended until 2006, after which it was completed and brought up to a minimum-controlled

\textsuperscript{50} which fiasco involved a totally different, much bigger, and really primitive Russian-designed “RBMK” reactor much like Hanford’s very first “production” reactor. Unlike Hanford’s, it was “dual purpose”—operated in a way (low fuel burnup/cycle) that generated both electricity and bomb-grade plutonium. Unfortunately, it was both manned and managed by schedule-driven, good team players who deliberately went about setting up about the only situation that could have possibly caused that accident. It wasn’t really their fault because the reactor’s fatal weakness (graphite-tipped control rods) constituted a state secret too important to reveal to its lowly “operators”.

\textsuperscript{51} Which, in light of the world’s rapidly deteriorating political/economic situation, is pretty scary and may, eventually prove fatal to millions (billions?) of people if a technologically advanced nation’s leadership decides to start another world, not just regional, war.
power level for several years’ worth of testing. In 2014, it was finally connected to the grid and reached full power (800MWe) at the end of 2016, thereby reclaiming Russia’s ownership of the world’s most powerful “sustainable” reactor. Whether any of Russia’s LMFBRs were ever operated as breeders of anything but weapons-grade plutonium remains unknown because what goes in/out of its fuel reprocessing facilities remains as much a closely guarded secret as it was within the USA’s. However, there’s no reason to expect that they couldn’t operate in that fashion.

On the other hand, the USA’s perpetual dithering about what reactors should be/do has left its last, best, hope of regaining the lead with its own probably even-better designed LMFBR concept in nuclear purgatory for over two decades (Triplett 2012, Till & Chang 2011). GE Hitachi Nuclear Energy’s “Power Reactor Inherently Safe Module” (PRISM) is a “small”, modular, sodium-cooled fast reactor concept based upon the 20 MW e Experimental Breeder Reactor (EBR II) operated at DOE’s Idaho site (NRTS/INEL/INEEL/INL)\(^{52}\) from 1964–1994. Each individual 311 MW e core would be immersed in a pool-type containment vessel and fueled with metallic (not oxide) fuel. They would be inherently safe due to negative power reactivity feedback, large in-vessel coolant inventory, passive heat removal, below-grade siting, and very low (near atmospheric) operating pressure. The U.S. Nuclear Regulatory Commission stated that, “On the basis of the review performed, the staff, with the ACRS [Advisory Committee on Reactor

\(^{52}\) NRTS = National Reactor Testing Station
INEL = Idaho National Engineering laboratory
INEEL = Idaho National Environmental and Engineering Laboratory
INL = Idaho National Laboratory
Safeguards] in agreement, concludes that no obvious impediments to licensing design have been identified.” Unfortunately, none have actually been built and most of the people that had worked on developing both them and their electrometallurgical (aka, “pyroprocessing”) fuel recycling system retired over a decade ago (Till and Chang 2011).

5.3 Molten salt reactors

Over the long haul, the most promising way to sustainably power the world with nuclear reactors would be to switch from solid-fueled to fluid-fueled, molten salt (MSR)-type breeder reactors. The reasons for this include:

• Since their fuel consists of already ionized (ionic) salts, it cannot be damaged by ionizing radiation. The lifetime of solid fuels is limited by radiation damage to both the fuel “meat” and its cladding.

• Their much lower operational pressures (water cooled/moderated reactors operate at >1000 psi, MSRs would operate at <100 psi) translates to a much lessened explosion potential (greater safety)\(^{53}\) and much lower construction costs (less steel, concrete, etc.)

• Greatly simplified fuel clean up, and recycling because “spent” fuel would not have to be dissolved to purify it and no complex/expensive solid fuel assembly would then have to be made from it.

\(^{53}\) For instance, an operating full-sized boiling water reactor (BWR) contains about 35,000 gallons of ~275°C water. The sudden release of that water would generate an approximately 0.04 kilotonne (40 tonnes of TNT) explosion.
• Higher temperature operation (500–700 vs 250–300 °C) translates to higher heat-to-electricity conversion efficiencies, more compact/cheaper gas turbines, less waste heat, and much more efficient operation in water stressed regions where air cooling might be necessary.

• Easier/simpler/cheaper fuel cleanup/recycle would facilitate the “burning” of the long lived transuranic isotopes (TRU) currently rendering radwaste management especially “controversial”

• Their highly negative temperature reactivity coefficients translate to intrinsically safer operation and superior “load following” capability (as more heat energy is withdrawn from the fuel salt by heat exchanger(s), they produce more heat and vice versa\textsuperscript{54}).

• Because fissile can be added whenever it’s needed, MSRs would not have to be started up with a huge excess reactivity (extra fissile) – again, this would tend to enhance safety\textsuperscript{55}.

Conceptually, the only things required of a molten salt reactor is that its fuel be brought into a critical configuration within its core and the resulting heat energy removed from it. Thus they could be built in many

\textsuperscript{54} Pulling heat energy out of (cooling) a molten salt causes a volumetric contraction of 200-400 ppm/degree C depending upon its composition. Since the internal volume of the core tank containing it decreases considerably less per degree, cooling increases the amount of fissile within the core which, in turn, increases its heat output thereby constituting a negative feedback mechanism. Conversely, removing less heat tends to reduce the reactor’s power output.

\textsuperscript{55} The reason for this is that gradually adding fissile (e.g., pellets of $^{235}$UF$_3$) to a molten fuel salt slipstream would be simple. That would also make it relatively easy/safe to initially start up an experimental MSR.
different ways, which explains the diverse array of concepts proposed during the past six decades.

Heat removal is critically important for any powerful nuclear reactor. Many ways have been proposed to achieve it with MSRs including:

1. Pumping a liquid coolant such as lead, mercury or a volatile salt directly into the fuel salt so that it can mix with and thereby extract heat from it (extensively investigated and deemed impractical)

2. Pumping a second molten salt or other coolant through pipes immersed in the fuel salt while also pumping it to enhance convective cooling on their outside surfaces

3. Pumping the fuel salt through external heat exchangers

To date, only loop cooled and integral-type\(^{56}\) pumped fuel salt concepts have been considered sufficiently practical to justify further consideration (Holcomb 2011). “Fast” MSR (FS-MSR) concepts are more flexible in that they do not require moderating media within their core and can tolerate much higher fission product buildups which translates to lower fuel recycling/reprocessing costs. The fuel salt addition and salt cleanup portions of FS-MSR-based concepts introduce further configurational variability. Fueling options range from directly adding TRU fluoride or chloride salts obtained from a centralized processing facility to the local processing of used LWR fuel into actinide fluoride or chloride salts using close-coupled salt cleanup infrastructure.

\(^{56}\)“Integral” means that the primary heat exchanger is within the reactor’s containment vessel.
As of spring 2018, there are at least 13 different companies/organizations (“nuclear start ups”) championing various molten salt reactor concepts. The best review I’ve seen yet of what’s been going on recently is a Power Point Presentation made by ORNL’s Dr. David Holcomb to UK Office of Nuclear Regulation (Holcomb 2019). While their potential economic, safety and operating features are extremely attractive, none of them have actually been licensed, built, or operated yet.

5.3.1 MSFR

One of the Generation IV International Forum’s (GIFs) Advanced Reactor (World Nuclear 2018) potentially sustainable “Gen IV” concepts, EURATOM’s EVOL program’s “thorium burning” Molten Salt Fast Reactor (MSFR) is especially promising (Fiorina 2013). EVOL started its decision making with the same graphite moderated single fluid (no separate blanket salt stream) MSBR that ORNL had left off with three decades earlier but soon decided that an unmoderated two fluid (separate fuel and blanket) system would likely be superior. Due to the following constraints…

- Not excessively high salt melting points
- High salt boiling temperature (i.e., generate little pressure at the reactor’s operating temperature)
- Good thermal and hydraulic properties (fuel = coolant)
- Stable under irradiation
- Adequate solubility of both fissile and fertile components
- Low tough-to-manage/politically charged radioisotope generation
- Reasonable fuel/fertile salt stream cleanup/reprocessing options
- Low solvent salt neutron absorption and scattering cross sections
…both its fuel and blanket salt streams would be a relatively low melting \( (565^\circ C) \) eutectic consisting of 77.5 mole\% \(^7\text{LiF}\) and 22.5 mole\% total actinide fluoride(s). The actinides within its fuel salt stream would be about 88 mole \% \(^{232}\text{ThF}_4\) (natural thorium – its "fertile" material) and 12 mole \% \(^{233}\text{UF}_4\) (its fuel/fissile). Its blanket salt’s actinides would comprise almost entirely natural \(^{232}\text{ThF}_4\).

Thorium’s “breeding” reactions are as follows:

\[
\begin{align*}
^{233}\text{U} + \text{neutron} & \rightarrow \text{two fission product atoms} + 2.49 \text{ neutrons} \quad \text{(Uranium 233, 2019)} \\
\text{One of the new neutrons} + ^{232}\text{Th} & \rightarrow ^{233}\text{Pa} \quad \text{(quick)} \\
\text{27 day half-life}& \quad ^{233}\text{Pa} \text{ slowly decays to form } ^{233}\text{U}
\end{align*}
\]

This reactor concept’s core is a 2.17 meter “square” (i.e., diameter = height) right circular cylinder surrounded axially by 1-m thick steel neutron reflectors, and radially by a 50-cm thick layer of fertile blanket salt, boron carbide layer, and a thick steel reflector. It is filled with the fuel salt with no core internal structures. The fuel circulates out of the core through 16 external loops, each one including a pump and a heat exchanger. A geometrically safe\(^{57}\) overflow tank accommodates salt.

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\(^{57}\) Geometrically safe means that the vessel is too small in at least one dimension to prevent so much neutron leakage that any amount of fissile within it could achieve criticality; i.e., enough of the new neutrons generated by each fission encounter enough other fissionable atoms to keep the reactions before they either escape (leak) or are absorbed/removed by something (a "poison"). A spherical shape is “worst” in this respect because its surface area (leak area) is minimal relative to its volume. Another way to prevent criticality is to prevent enough fissile atoms to accumulate in any one place regardless of what else might be in or around it. A third is to assure that whatever space containing the fissile also contains plenty of “poison”, e.g., anything containing boron, cadmium, etc. In this respect, pure water is especially “bad” because its high hydrogen content “moderates” the speed of freshly formed neutrons which greatly increases the probability that they will absorbed by other fissile atoms before they can wander (leak) out of the vessel. For example, ORNL’s LOPO aqueous homogeneous reactor (GOOGLE it) achieved criticality with just 580 grams of \(^{235}\text{U}\) dissolved up in about 14.6 liters of water.
expansion/contraction due to temperature changes. A salt draining system connected to the bottom of the core allows core dumping to passively-cooled criticality-safe tanks to facilitate maintenance or respond to emergencies. This system includes freeze valves that would melt as soon as electric power is lost or the salt seriously overheats. The entire primary circuit, including the gas reprocessing unit, would be contained within a secondary reactor vessel. Fig. 11 is a schematic of its primary loop’s layout and Table 6 summarizes its core parameters.

On the other hand, a critical mass of solid metallic $^{235}$U (no moderator present) would weigh ~52,000 grams & occupy about 2.8 liters (i.e., would contain about 484 x more fissile atoms/cc).
After pondering Dr. Fiorina’s presentations at GLOBAL 2013, I wrote an open access paper (Siemer 2015) describing the especially attractive features of an “isobreeding” (generates only as much new fissile ($^{233}$U) from “fertile” $^{232}$Th as it “burns”, no extra) version of that concept. Isobreeding constitutes an especially relevant goal/assumption because, at steady-state, the world would not need extra fissile, which fact would mitigate proliferation concerns. Isobreeding would also greatly simplify/cheapen that reactor’s operation because very little “reprocessing” of its salt streams (6 to 10 liters per day) would be required to keep it running at steady-state fed with nothing other than natural thorium (see APPENDIX II).

**Table 6: MSFR core parameters (Fiorina 2013)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal/electric power</td>
<td>3GWt/1.5GWe</td>
</tr>
<tr>
<td>Fuel salt volume</td>
<td>18m$^3$</td>
</tr>
<tr>
<td>Fraction fuel within core</td>
<td>50%</td>
</tr>
<tr>
<td>Number of heat exchange loops</td>
<td>16</td>
</tr>
<tr>
<td>Fuel salt flowrate</td>
<td>4.5m$^3$/s</td>
</tr>
<tr>
<td>Salt velocity, 0.3 m diameter pipes</td>
<td>~4 m/s</td>
</tr>
<tr>
<td>Blanket thickness</td>
<td>0.5 m</td>
</tr>
</tbody>
</table>

**Figure 12: The EU’s Molten Salt Fast Reactor (MSFR)**
<table>
<thead>
<tr>
<th>Blanket /volume</th>
<th>7.3 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boron carbide shield thickness</td>
<td>0.2 m</td>
</tr>
</tbody>
</table>
It would operate at 700-750°C allowing the use of a supercritical CO$_2$ working fluid (not water) in compact$^{58}$ Brayton cycle turbines featuring overall thermal-to-electric energy conversion efficiencies $\approx 50\%$. Fluoride-based molten salts have very low vapor pressures even at red heat (at atmospheric pressure, fluoride salt mixtures typically boil at around 1400°C), very high volumetric heat capacities (some are higher than that of water at a LWR’s $>$75 atmosphere working pressure), good heat transfer properties, low neutron absorption, aren’t damaged by radiation, chemically stable, do not react violently with air or water, compatible with graphite, and some are also inert to common structural metals.$^{59}$

5.3.2 MCFR

Another concept which apparently wasn’t formally considered by GIF, the Molten Chloride (salt) Fast Reactor (MCFR), should be simpler to build than the MSFR because its $^{238}\text{U}$-to-$^{239}\text{Pu}$ “breeding” cycle’s superior neutronics should permit isobreeding without a fertile isotope ($^{238}\text{U}$ or $^{232}\text{Th}$) containing “blanket” surrounding its core. That would significantly mitigate proliferation concerns because at steady-state neither the reactor itself nor its attendant fuel salt cleanup/recycling system would contain “bomb grade” fissile (>90% $^{239}\text{Pu}$) that might tempt perforce suicidal terrorists to attempt its “diversion”. Another of

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$^{58}$ They would weigh about one-fifth as much as a typical “low temperature steam”, Rankine cycle-based, LWR’s steam turbine.

$^{59}$ Many people confuse the fluoride anion (fluorine in its “happiest”, most stable, & therefore essentially inert state) with elemental fluorine (fluorine in its unhappiest, most reactive & most corrosive state) – they are as different as night and day.
its practical advantages is that its core could be situated within a tank containing either a molten bismuth/lead “reflector” or a molten blanket salt containing a fertile isotope which would allow it to breed

Figure 13: Terrapower’s MCFR  (https://www.energy.gov/ne/articles/southern-company-and-terrapower-prep-testing-molten-salt-reactor)

startup fissile for other reactors. Like most other MSR concepts, fission-generated heat energy within its fuel salt would be transferred to the working fluid (probably another molten salt) of an external heat exchanger (HX) and then to a secondary HX which then transfers it to its turbines’ working fluid (e.g., water for steam/Rankine or carbon dioxide for supercritical CO$_2$/Brayton). Reprocessing (the recovery and recycle of U & TRU) would entail the chloride-salt based technologies developed for the IFR (Malmback 2011). Since its reprocessing requirement would be small and sodium comprises most of the cationic material in its raffinates, everything except the TRU, U, and chlorine in the salt so-processed would be vitrified to compact, “best demonstrated available technology” (glass), waste forms suitable for eventual disposal. Its chlorine would be recycled to minimize waste volume, produce better
quality waste forms, and prevent escape/ dispersal of the otherwise problematic $^{36}\text{Cl}$.

These reactors would utilize chloride rather than fluoride salts because chlorine (a bigger atom) exhibits much less “moderating” capability and the trivalent actinides serving as both their fissile and fertile isotopes are more soluble in them than in their fluoride counterparts. Natural chlorine’s major isotope, $^{35}\text{Cl}$ (76%) gives rise to $^{36}\text{Cl}$ as an activation product – a long-lived energetic beta source, which means that if the system’s fuel cycle were to discard chlorine, it would complicate waste management. However, since chlorine discard is both unnecessary and unwise (Siemer 2012), a more compelling reason to use pure $^{37}\text{Cl}$ – based salts is that that $^{35}\text{Cl}$ has greater moderating (via scattering ) capability and would therefore reduce fissile breeding. Its transmutation would also generate a little $^{36}\text{S}$ which raises potential corrosion issues. In any case these are probably some of the reasons why the Bill Gates-backed TerraPower “nuclear startup” recently decided to split its reactor development efforts between its solid-fueled, liquid-metal cooled, “breed and burn”, “Traveling Wave” concept and an unblanketed, 

$^{60}$ The faster a reactor’s neutrons move, the better it can both breed and consume actinide isotopes not fissionable with slow-moving neutrons. Fission products possess relatively large neutron capture cross sections in the thermal (slow) energy range but much smaller ones at higher energies. Consequently, much greater fission product buildup is tolerable in an FS-MR than in a thermal-spectrum (moderated) MSR. Since chlorine is a bigger, heavier, atom than is fluorine, it’s a poorer moderator which is why a MCFR would be “faster” than its MSFR counterpart (in either system, halide atoms would outnumber the metals by about 1.8:1).

$^{61}$ Such corrosion is unlikely: $^{36}\text{S}$ would likely be either stripped out of the fuel salt as a gas or converted to a non-corrosive and easily removed solid compound via reaction with FP-type molybdenum.
chloride salt-based MCFR, see Fig. 4 (Southern 2018). Another startup, “Elysium”, appears to be proposing a similar system.

Both of those startups are currently proposing “breed and burn” versions of their MCFRs to render them more attractive to regulators and utility owners. Breed and burn translates to requiring a much simplified (and less effective) fuel salt “cleanup” system – salt seeking FP are not continuously removed\(^\text{62}\), which means that the reactor will eventually have to be shut down and that salt either replaced or “reconditioned” (see APPENDIX III). Regulators like breed and burn because it would be easier to regulate (they would only have to show up en mass during fuel exchange periods). Utilities like it because it would simplify reactor operation and therefore probably save them money over the short haul.

Because “breed and burn” compromises reactor performance in order to simplify operation, it would require more startup fissile which in turn would limit the rate at which sustainable reactors could be built. Let’s go through an example.

Figure 14 depicts net “effective neutron multiplication factor (\(k_{\text{eff}}\))” (“reactivity”) as a function of time of a “breed and burn” MCFR concept described in one of Terrapower’s artfully written patent applications\(^\text{63}\).

\(^{62}\) However, gaseous and noble metal FP scum/”smoke” would be continuously removed.

\(^{63}\) Terrapower “publishes” only in the patent literature. Like most patent applications and, unfortunately, the ABSTRACTS of many paywalled scientific publications, it’s written to claim as much as possible while revealing as little technical information as possible. This section’s goal is to demonstrate how such perforce “open access” information can be used draw conclusions about reactor concepts – not determine exactly whatever Terrapower (or Elysium) is currently proposing. My effort’s 65+ cubic meter core volume figure matches that mentioned elsewhere within that patent disclosure (see APPENDIX III for a further discussion).
(Latkowski 2016). The words characterizing it don’t specify its shape (probably right circular cylindrical), size, or how it would be controlled but does disclose the following:

“FIGS. 1A-1F utilizing the 66NaCl-34UCl₃ composition. Curve 502 depicts a modeled k-β curve for a power level of 5800 MW and curve 504 depicts a modeled k-β curve for a power level of 3420 MW. It is noted that both curves 502, 504 are modeled to operate with a depleted uranium (DU) feed and without specific lanthanide removal. As shown in FIG. 5, the 3420 MW case (curve 504) may operate for nearly 70 years before going subcritical, while the 5800 MW case (curve 502) may operate for approximately 41 years prior to going subcritical. In addition, the model shown in FIG. 5 also predicted a fuel burnup of 43% without any lanthanide removal during the years of operation. Thus, modeling shows that chlorine-based uranium fuel salt may be effective at reducing dependencies of prior molten salt reactors on enriched uranium to maintain criticality.”

Another statement in that application says that, “a fuel salt having a $^{235}$U content of 10 mol % may have a reactor core section volume of approximately 67 cubic meters ($m^3$)”. Another says that the reactor’s initial U enrichment level) would be such that its separation wouldn’t raise proliferation concerns, i.e., be under 20% $^{235}$U.
Figure 14: TERRAPOWER’s Breed and Burn concept’s $k_{\text{eff}}$ over time

In order to translate such-written technical information to something meaningful to someone trying to decide whether or not the concept makes sense, it’s necessary to combine it with some technically reasonable educated guesses.

Here goes:

First, generating 3420 MWt for 70 years (Fig. 9’s curve 504) adds up to 7.55E+18 heat-type Joules \[3420E+6\times3.15E+7\times70\].

If 45\% of that heat is converted to electricity (reasonable), that’s 107.7 GW$_e$ years’ worth of electrical energy \[7.55E+18/1E+9/3.15E+7\]

Since a single fission event generates about 3.2E-11 J (\~200 Mev) and one gram mole of $^{235}$U comprises 6.023E+23 atoms (Avogadro’s number) the total amount of uranium consumed during that “burn” comes to about 92 metric tonnes \[7.55E+18*235/3.2E-11/6.023E23/1E+6\]

Next, I will assume that the reactor’s reactivity is maintained at $k_{\text{eff}}$ = 1 (i.e., it’s “controlled”) by adding a 34/66 mole percent depleted UCl$_3$/Na$^{37}$Cl mixture which pushes the same volume of its “too-hot” fuel salt into a critically safe overflow tank$^{64}$. I’ll also assume that the

$^{64}$ Any reactor’s “effective neutron multiplication factor” ($k_{\text{eff}}$) must be maintained at almost exactly 1.00 or it’ll either “die” ($k_{\text{eff}} < 1$) or become supercritical ($k_{\text{eff}} > 1$) which could possibly lead to an explosion. Since each individual neutron absorption/fission occurs far more quickly than either human or automated control systems can respond, all practical reactor concepts rely upon natural negative feedback mechanisms (e.g., Doppler broadening & thermal expansion) for stability all of which can work because a fraction of the neutrons (“delayed neutrons”) generated per fission aren’t immediately released.
amount of uranium so added is equal to the amount of fissile consumed via fission, i.e., 92 tonnes.

If 92 tonnes represents 43% of the total uranium fed to the reactor during its breed and burn cycle, the grand total must have been 214 tonnes (92/0.43) which suggests that that reactor’s core must have started out containing ~122 tonnes (214-92) of uranium.

Application of the principle of “additive molar volumes” (see APPENDIX IV and ORNL3913, p 27) permits one to calculate that this fuel salt mix would possess a density of about 3.64 g/cc and that each cc of it would contain about 1.89 g U. This means that the volume of fuel salt within the reactor’s core is about 65.6 m$^3$ [122E+6/1.89/1E+6], which translates to a 5 meter diameter spherical or 4.36 meter “square cylindrical” core.

Next, since it would be impossible for a reactor containing a 34/66 molar mix of trivalent uranium and sodium chloride salts to simultaneously possess “a $^{235}$U content of 10 mol % with uranium that’s under 20% enriched”$^{65}$, I’m going to assume that the folks who wrote Terrapower’s patent application meant to say that their example’s reactor’s uranium’s enrichment level was 10%.

If initial enrichment is 10%, that translates to 12.26 [0.10*122] tonnes of startup fissile ($^{235}$U).

If we next assume that the depleted uranium coming out of the enrichment plant has 0.15% $^{235}$U in it, the amount of 0.71%$^{235}$U, NU

$^{65}$ 20% of 34 mole% = 6.8, not 10 mole% $^{235}$U
needed to make 12.2 tonnes of $^{235}$U fissile would be about 2178 tonnes $[12.2/(0.0071-0.0015)]$. That’s 20.2 $[2651/107.7]$ tonnes of NU consumed/GWe which is about eight times $[160/20.2]$ less than that required to generate the same amount of electricity with state-of-the-art LWRs.

If the reactor’s initial $^{235}$U enrichment level were 20% rather 10%, its first breed and burn cycle would be 4 times more fuel efficient than a LWR’s.

It’s not a real breeder but is indeed much more fuel efficient than are almost all of today’s power reactors (the likely exceptions being Russia’s LMFBRs). Additionally, since the reason that it would eventually “die” after 70 years is that it has become choked up with fission product “poisons”, its “spent” salt contains more than enough fissile to operate the same reactor once that FP is removed. This means that this concept does indeed represent something that could become a genuinely sustainable system.

That plus the fact that “breed and burn” would allow decision makers to kick the politically charged “reprocessing” can on down the road for another half century or so makes it pretty attractive.

Again, I feel that their main drawback is that breed and burn reactors would require a fairly large amount of startup fissile. In this example, it would be 7.93 tonnes/GWe ($12.2/(107.7/70)$) which means that going that route would likely limit the rate at which a sustainable nuclear renaissance could replace fossil fuels and wind/solar/biofuel/slave labor-based substitutes.

5.3.3 MOLTEX
Another promising MSR concept not considered by GIF is MOLTEX’s “stable salt reactor” (Moltex 2018). Its primary technical distinction is that its core consists of bundles of thin-walled steel tubes containing the fuel salt immersed in a big tank of coolant salt. The fuel salt within those tubes contains a fissile isotope (any combination of trivalent $^{239}$Pu, $^{235}$U, and/or $^{233}$U) in a molten chloride-based solvent salt containing a fertile isotope (typically $^{238}$UCl$_3$) and table salt (NaCl). Unlike the other concepts I’ve mentioned, its fuel salt would be “static”, not continuously recirculated between its core and external heat exchangers. Fission-generated heat energy would pass through the walls of those tubes$^{66}$ to a rapidly upwards moving (pumped) fissile-free surrounding, fluoride-based coolant/blanket salt comprised (in breeder versions) of a ThF$_4$-NaF eutectic$^{67}$. The coolant stream’s heat energy would be transferred to a third molten salt stream (e.g., “solar salt” a low melting (eutectic) mix of sodium and potassium nitrates) which, in turn, would exchange its heat with water or CO$_2$ to generate the high pressure gas driving its power turbines. Both its fuel and primary coolant salt streams would be rendered non-corrosive to conventional stainless steels via redox buffering with divalent Zr – an extremely powerful reducing agent and fluorine/oxygen scavenger. In this writer’s opinion, the MOLTEX concept’s chief virtue is that it should be considerably easier and cheaper

$^{66}$ This concept’s “eureka moment” was the realization that in the Earth’s gravitational field, a nominally static fuel salt contained within thin-walled (~0.05 cm), ~1 cm diameter steel tubes similar to those typically used in LMFBRs, could transfer their heat to an external coolant sufficiently rapidly (Scott 2014). The reason for this is that the density gradients caused by the fuel salt’s internal heat generation (~50 kW/liter) would generate a great deal of local turbulence enabling rapid convective (not just diffusional) heat flow from the tube’s contents to its walls.

$^{67}$ Non breeders would utilize a NaF/ZrF$_4$ eutectic (minimum-melting mixture) coolant salt.
to implement a “first of a kind” (FOAK) breeding-capable version of it than either the MCFR or MSFR.

The reasons for that include:

1. Building and operating one would not require exotic materials
2. It’s intrinsically “small and modular” (each 150 MWe/module weighs about 18 tonnes – see Fig. 15) meaning that its parts could be factory fabricated/trucked to a build site and that a MOLTEX-type reactor could easily be scaled up to produce as much power as needed (stack additional modules side by side in a common coolant salt tank)
3. It’s apt to be easier to convince both the government’s decision makers and investors that building one wouldn’t be too risky

![Figure 15 Relative sizes of MOLTEX (MSR) & NUSCALE (LWR) “small modular reactor” modules](image-url)
Regarding point # 3, regulators would be comforted by its simplicity (there’s nothing mysterious about how it would work and it’s not very complicated) and the fact that couldn’t possibly suffer either a Fukushima-like meltdown (upon shut down, its core would be air cooled via natural convection – no huge water pools and pumps needed) or a Chernobyl-like steam explosion (no water). Investors are apt to like the fact that it should be possible to build one both quickly & cheaply.

As far as I am concerned, another significant plus is that its developers are willing to reveal more “technical details” than do most of their competitors in today’s MSR startup sweepstakes (Scott 2014). Credibility in this hyper secretive technical arena is tough to earn and roughly proportional to the degree to which a concept's champions embrace "openness".

Its primary technical downsides are its large startup fissile requirement (my calculations suggest ~12 tonnes/GWe) and that each reprocessing cycle would require the refabrication of roughly the same number of individual fuel tubes as would an equally powerful LMFBR. However, also like the LMFBR, its high (~150 GWt/day) fuel burnup per cycle means that it would require only about 10% as much reprocessing/ refabrication as would breeding-capable (thorium-burning, heavy water moderated) PWR, BWR, or CANDU reactors. Apparently a political downside as far as US DOE’s NRC is concerned is the same characteristic that has helped render its radwaste management programs so intractable; i.e., “it wasn’t invented here”.

The MSR concepts I’ve described so far are all “fast” because their cores would not contain a moderating material (e.g., liquid water, beryllium oxide, zirconium hydride, or elemental carbon) to deliberately slow the rapidly moving (fast; i.e., > 1 MEV) neutrons initially generated by nuclear fission. As also previously mentioned (it bears
repeating), this enables superior fuel (fissile) regeneration capability, lessens minor actinide (Am, Cm, etc.) build-up, and would permit operation with much higher fission product “ash” salt concentrations which, in turn, translates to a much lessened fuel salt reprocessing (clean up) requirement. No moderator also means that their therefore relatively small cores could be “modular” (transportable) and that they would not generate ~75 tonnes/GWe of irradiated/contaminated/damaged moderator radwaste per year. To date, the world’s graphite-moderated “production” (of weapons grade plutonium) reactors have generated roughly 250,000 tonnes of radiologically contaminated graphite, most of which lingers in “temporary” storage (TECDOC 2010). In principle, if they were to be operated properly (sustainably), any of them would convert almost all of their actinides, both those introduced and generated in-situ via neutron capture/transmutation, to relatively short-lived, simple-to-manage, fission products (FP). All of them would obviate the cost, waste, and safety-related issues inherent to potentially sustainable, solid-fueled reactor concepts such as the sodium-cooled “Integral Fast Reactor” (IFR), “Traveling Wave” concepts or General Atomic’s helium-cooled “Energy Multiplier Module (EM2) (Rawls 2010). All of them should be cheaper to build than “advanced” versions of today’s dominant light water reactors because they would operate at much lower/safer pressures and generate more useful (higher temperature) heat energy. And finally, all of them could be started with fuel comprised of the uranium, plutonium and minor actinides (TRU) extracted from spent LWR fuel assemblies which would simultaneously simplify/cheapen the long-term management of such “waste”.

Since there isn’t enough $^{235}\text{U}$ or spent LWR fuel-derived plus “excess” weapons-grade plutonium in the world (roughly 2400 tonnes total) to start more than 400-600 of any sort of fast breeder reactor, they would
have to be configured to breed extra start-up fissile until enough of them had been built to reach steady state (power everything).

5.3.4 Tube in Shell Thorium Breeder

Figure 16 depicts another concept that no one currently seems to be considering that may prove to be the “best” one. It’s the “semi fast” (intermediate neutron speed) tube-in-shell configured, two-fluid thorium breeder reactor described by David LeBlanc a dozen years ago (LeBlanc 2007). Its internal core (aka tube) contains a fuel salt comprised of a low melting 2 to 1 mole-wise solvent salt mixture of $^7$LiF and BeF$_2$ (FLiBe) containing a surprisingly small amount of fissile (about 0.16 mole% or 6.1E+19 atoms/cc of $^{233}$U) and no fertile $^{238}$U or $^{232}$Th. The outer (aka, shell or tank) side of the system contains a blanket salt comprised of 25 mole % ThF$_4$ + 75 mole % LiF. Virtually all of its heat-generating fission reactions take place within the core but sufficient of the neutrons so produced pass through the wall separating it from the blanket salt to regenerate at least as much new fissile as is burned within it (the fission of $^{233}$U generates two fission product (FP)
elements plus an average of 2.48 neutrons\(^{68}\). About 1.15 of those neutrons are absorbed by other \(^{233}\)U atoms within the core salt thereby keeping the reaction going and producing a relatively small amount of \(^{234}\)U therein while the remaining ~1.33 are absorbed by the system’s internals (wall metal, \(^{7}\)Li, Be, F etc.) plus the blanket salt’s thorium.

It is a stretched-out version of the 4 foot core diameter, 2 fluid reactor (number 36) in Table 3 of ORNL 2751 (Alexander 1959). It is cylindrical rather than spherical with a diameter (48 inches x 0.78 or 95 cm) relative to ORNL’s original concept which emulates its neutronic characteristics (0.78 is the long-cylinder to spherical “geometric buckling factor”\(^{69}\)). Its core is long enough (7.4 meters) to contain sufficient fuel salt (5.24 m\(^3\)) to limit mean heat generation within it to 400 kW per liter, which translates to a whole core heat generation of 2.1 GWt \([4E+5*7.4*(0.95/2)^2*1000]\) or, assuming 48% efficient thermal heat to electricity conversion, 1.0 GWe. Assuming \(^{233}\)U, its within-core startup fissile requirement would be 124 kg \([=6.1E+19*1000*5.24*233/6.023E+23]\) which, if it were connected to a total of 8 m\(^3\) worth of external piping and heat exchanger(s), translates to a total startup fissile requirement of 312 kg \([124*(8+5.24)/5.24]\) – well under 10% of that required by any of the “fast” reactors I’ve already

\(^{68}\) What revived this concept to me is that, 1) both fuel and blanket salt reprocessing would be simpler than that required by any of the U/Pu based MSR concepts I’ve seen, and 2) \(^{233}\)U fission apparently releases about 10% more new neutrons than ORNL’s researchers assumed six decades ago. (Uranium 233, 2019)

\(^{69}\) A geometric buckling factor relates the shortest possible dimension (usually diameter) of a non-spherical reactor to one that is spherical. Spherical vessels possess the lowest possible surface area to volume ratio which means that they minimize neutron leakage/loss.
described\textsuperscript{70}. That’s a crucially important point because the availability of startup fissile limits the rate at which a big-enough sustainable nuclear renaissance could be implemented.

Since this concept’s fertile ($^{232}$Th) isn’t mixed in with its fissile ($^{233}$U)…

1) thorium would not have to be separated from REE-type FP - U is easy/cheap to separate from the rare earths (and Pu), Th isn’t

2) because fertile atoms would not be absorbing neutrons within the core, achieving criticality therein would require relatively little fissile (that’s why it wouldn’t require much startup fissile)

3) fuel salt clean up/reprocessing would be much easier/cheaper than it would have been with the MSBR\textsuperscript{71} or today’s LFTR concept: simply fluorinate out/collection the uranium, distill off/collection the FLiBe, & throw away everything else. The remaining waste would be easy/cheap to vitrify and there wouldn’t be much of it.

\textsuperscript{70} As is the case with everything else I’ve written about “other people’s” concepts, this section was sent off to Dr. LeBlanc to review and, if necessary, correct. As is also usual, people cc’d on my note seized upon that opportunity to point out that (unlike their own concept), this one is “impossible” because of its inconsistency with today’s rules and customs. For instance: “Main issue is ...proliferation concerning reprocessing of both core and blanket. With the MSBR/LFTR required reprocessing system U fluorination system it is trivial to get pure HEU233 with absolutely NO U232 ... 100% U233 critical mass is about the same as 93% Pu239, and far lower than 93% U235, the currently used weapons main arsenal materials. “. In other words, in that reviewer’s opinion, the purpose of NE R&D is to devise something that nobody could come up with a hypothesized show stopper based upon the notion that the future’s civilian power reactors would be operated by unsupervised homicidal idiots.

\textsuperscript{71} MSBR = ORNL’s graphite-moderated, breeding-capable, single-salt reactor concept (Robertson 1971)
Another of this concept’s advantages is that its blanket could contain enough fertile Th to effectively shield $^{233}\text{Pa}$ from neutrons until it decays to $^{233}\text{U}$ (the LFTR’s (see below) relatively small blanket salt volume along with its slow-moving neutrons, renders $^{233}\text{Pa}$ separation/storage necessary for breeding)

**ORNL** published several papers having to do with recovering most of the $^7\text{Li}$ & Be from some of its proposed fuel salt compositions via a simple one-plate distillation (Scott 1966). It worked fine for that purpose but wasn’t of much use for separating thorium from $^{90}\text{Sr}$ and REE-type FP.

### 5.3.5 LFTR (liquid fluoride thorium reactor)

Here’s another possibly sustainable MSR concept along with two others more suitable for niche applications.

The “Liquid Fluoride Thorium Reactor” (LFTR) is a revival of the graphite-moderated, graphite-constructed, two fluid breeder (core fuel salt surrounded by a separate blanket salt) described by ORNL’s nuclear engineers after it had been concluded that such a system would be virtually impossible to build (Robertson et al, 1970). The LFTR’s chief advocate, Kirk Sorensen\(^\text{72}\), has apparently come up with a proprietary

\[^{72}\text{Kirk has probably done more than anyone else to revive interest in MSRs. Circa 2006 he paid ORNL’s document control people to “clear”, copy, and then send him its MSR-relevant research reports which he immediately posted on his “Energy from Thorium” blogsite. Those documents along a great deal of other such literature remain there freely available for anyone, “friend or foe”, to sift through. Yeah Kirk!}\]
(secret) way to get around that issue. Like all moderated (~thermal spectrum) MSRs, its core would consist of a big block of graphite with relatively small salt channels through it, top-to-bottom. In its case, there are separate actinide-bearing fuel (mostly $^{233}$UF$_4$) and fertile (ThF$_4$) salt channels. Both of them share a common low-melting (eutectic) solvent, FLiBe ($67\% \ ^7$LiF, 33% BeF$_2$).

It’s not getting much attention from reactor experts for several reasons:

1) It would be a genuinely sustainable, graphite moderated, two-salt MSR which means that its purpose, fabrication and operation would be different than that of any of the reactors adopted/championed by the USA’s industry and government after Weinberg was downsized.

2) Among those decision makers’ beliefs is the notion that a reactor’s owner/operators should not have to run a close-coupled fuel cleanup/recycling system and manage the waste stream that it would generate. Today’s once-through nuclear power systems are extremely simple/convenient in both respects (throwing empty beer cans out of your car’s window is also simple/convenient).

3) Because 27day half-life $^{233}$Pa has a significant thermal neutron absorption cross-section, any thermal spectrum Th/U fuel cycle presents a distinctive proliferation issue because a CR $>1$ is impossible if $^{233}$Pa is not continuously removed and allowed to decay in a separate, low thermal neutron flux, environment. Consequently, a breeding or even breakeven-capable LFTR would require far more “reprocessing” than would any fast thorium-fueled, breeding-capable MSR like the EU’s MSFR or Elysium & Terrapower’s chloride salt-based concepts and would therefore be considerably more troublesome/expensive to operate.
4) Like any graphite moderated reactor, LFTRs would generate 75-100 tonnes of “crapped up” waste graphite (moderator) per GW\textsubscript{e}-year – fast MSR breeders wouldn’t\textsuperscript{74}.

5) As would also be the case with the MSFR, it would be breeding-capable only if its fuel salt were made with isotopically pure $^7\text{Li}$, not natural lithium.

6) As would the blankets of any sort of breeder, its blanket salt would definitely contain “bomb” grade fissile (almost pure $^{233}\text{U}$) that our officials’ imaginary terrorists could divert.

7) And, probably most important in the real world, no one like Bill Gates or Jack Ma has been convinced to support LFTR development.

The LFTR’s chief virtue is that if it actually could be made to work, it would require considerably less start up fissile than would the LMFBR (IFR) or any sort of equally powerful FS-MSR with the exception of Figure 16’s tube-in-shell concept.

**5.3.6 THORCON and IMSR**

Several other MSR concepts are currently vying for venture capitalist and government money/attention. From what I’ve been able to gather, their designs were apparently force fit into compliance with today’s light water reactor rules and assumptions resulting in systems little if any more fuel efficient than are today’s LWRs\textsuperscript{75}. In my opinion while it

\textsuperscript{74} “crapped up” means heavily radiologically contaminated.

\textsuperscript{75} Most of the USA’s nuclear startups focus upon developing salable IP rather than saving the world. Their “products” of course must be “protected” for as long as possible and I can’t really
might be fun to think about how we might go about turning a ballerina into a hippo\textsuperscript{76}, it is a distraction that the best and brightest among us shouldn’t be concerning ourselves with in light of the issues that Hubbert, Weinberg, and Hansen identified decades ago.

Reactors concepts that couldn’t “save the world” would, however, be suitable for some important niche applications; e.g., powering big ships or isolated small/medium sized cities. If the fissile fueling them were to be generated by the breeder-type reactors powering everything else, they could constitute an important part of a sustainable overall system.

One such reactor would be THORCON’s “doable” MSR (http://thorconpower.com/). It is a high energy density, graphite-moderated, molten salt converter with a rather short (4 year) moderator lifetime when run at its full power rating. It’s “doable” because it emulates ORNL’s already-demonstrated/proven MSRE (MSRE 2018) in a manner that wouldn’t require exotic metals to construct or isotopically pure $^7$Li to run. A land-based THORCON plant would consist of barge transportable 250 MWe modules, manufactured on an assembly line like WWII’s liberty ships. Each module would consist of two 400 ton “cans” each of which houses a 250 MWe primary loop including a “pot” (reactor), pump and primary heat exchanger. The cans are duplexed

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\textsuperscript{76} The problem with the "doing something is better than doing nothing" argument for designing performance compromised systems is that once we humans (esp. businessmen) get used to doing anything in a particular fashion, everyone involved with implementing our business model resist change. Since people supplying important things tend to get rich, they also become able to influence politicians to support their business model which, in turn, generates rules, laws and bureaucracies constituting the “barriers to science” that stifle progress/change.
meaning that when one is operating, the other is in cool-down or stand-by mode. The plant is designed so that the change-out of a cooled-down can would be both simple and quick. At that time it would be lifted from its silo, moved by the plant’s crane to a disassembly area, and those portions of its primary loop requiring replacement remotely separated and stored.

The baseline THORCON would use a NaF-BeF$_2$ (nabe) solvent salt mixture for both its radioactive fuel and non-radioactive secondary salt streams because it is already available and reasonably cheap. Since nabe is less attractive neutronically than is a $^7$Li based salt (FLiBe), it would be only about twice, not 140 times, more fuel efficient than are today’s LWRs$^{77}$. The baseline version would employ a tertiary loop using solar salt (a low melting eutectic of sodium and potassium nitrate salts) to remove essentially all of the tritium generated during operation. All the fluid loops within the system are designed to generate natural circulation driven by decay heat in the event of loss of power. Both the secondary and tertiary loops are located in an exterior-to-the-can steam generating cell designed to contain a massive rupture anywhere within these loops. Given a rational regulatory environment, it should be able to generate electricity for between 3 cents and 5 cents per kilowatt-hour.

Another well-publicized “doable” MSR reactor concept, Terrestrial Energy’s “IMSR” would probably be easier to turn into a ship’s engine $^{77}$

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$^{77}$ There are a number of straightforward changes that would improve THORCON’s “fuel economy”. Simply switching from nabe to FLiBe would increase it by around 20%. Turning it into a genuine breeder would require either running it with HEU (undiluted $^{233}$U) and close-coupling it to an onsite reprocessing plant OR converting it to a fast reactor by eliminating the graphite (Jorgensen 2019).
Like THORCON’s concept, it is “integral”, compact, graphite moderated, and no fertile-containing “breeding” blanket surrounds its core. However, it’s more conventional in that the fertile isotope accompanying the fissile \(^{235}\text{U}\) fueling it is \(^{238}\text{U}\), not \(^{232}\text{Th}\), which substitution renders it no more fuel efficient than are today’s civilian power reactors.

“Little” reactors like these compare favorably with the huge diesel engines currently powering large ships. The diesel engines propelling the world’s international shipping industry currently burn about 298 million tonnes of “oil” per year (ICTT 2019). At 42kJ/gram, that comes to 1.25E+19 J worth of heat energy per annum. Since state of the art shipping-type diesel engines are a bit more thermally efficient than are THORCONs or ISMRs (~50 vs ~45%), that’s equivalent to ~1.39E+19 J’s worth of nuclear-type heat energy. When bunker fuel oil costs $600/tonne, that engine’s fuel cost works out to about 10.3 cents per kWh or 3–5 times more than that reactor’s power should cost. Each 250 MWe THORCON “can” weighs 400 tons \(^{78}\) or about one sixth as much as a 50% thermally efficient Wartsilla 81 MW engine (currently the world’s biggest and most efficient diesel engine). Each such can should be able to continuously power a big ship for about 12 years \((250/81*4)\) which means that a two-can module could probably power it throughout its entire life time. Those savings would really add up: over a 24 year working life time: a 50% thermally efficient 81 MW diesel engine would consume 2.93 million tonnes of bunker fuel, which at $600/tonne would cost $1.76 billion of today’s dollars – reducing that cost by two thirds

\(^{78}\) The gas turbine that would actually power the ship would weigh considerably less than the reactor.
would give that ship’s owners/investors a very warm feeling. It would also let them honestly claim that their decision to so power their ship reduced the amount of CO₂ that would have otherwise been dumped into the environment by 9.2 million tonnes. It would also eliminate another environmental impact because bunker fuel is extremely dirty compared to the diesel fuels used in land-based trucks, cars, and tractors, meaning that big ships currently dump more SOx into the environment than do any of Mankind’s other fuel burning machinery and/or processes.

Since the 22 TW’s worth of breeder-type reactors powering my scenario’s clean, green, and prosperous future world would also exhibit about 50% thermal-to-electricity efficiencies, they would be consuming 44 TW’s worth of fissile. That’s’ 1.39 E+21 J [44E+14*3.15e+7] of nuclear heat per annum for “everything else” which figure happens to be ~100 times that required to power today’s shipping fleet with “small” converter-type reactors. This in turn suggests that if the big breeders generated 1% more fissile (CR=+1.01) than they consumed, their extra fissile could power international shipping too.

5.3.7 The history, whys, and hows of sustainable reactors
All MSR breeder concepts save MOLTEX are at least 50 years old. No potential breeder except the USA’s pet solid fueled, “liquid metal (cooled) fast breeder reactor” (LMFBR) technology ever received sufficient attention/funding to generate anything but “paper” (conceptual) reactors with, again, one exception – Dr. Weinberg’s/ORNL’s graphite moderated “molten salt reactor experiment” (MSRE) which operated for ~four years during the mid-late 1960’s (MSRE 2018). However, that MSR couldn’t “breed” for
economic reasons - it was too small (8 MWt) and its core was not surrounded with a blanket containing additional fertile $^{232}\text{Th}$. That R&D program ended circa 1973 because a financially strapped US federal government (the Vietnam War had been fought with borrowed money thereby ballooning its national debt and triggering severe inflation) decided to fire the bothersome Dr. Weinberg (Weinberg 1994) and “study” only the LMFBR concept because it’s a much better bomb-grade plutonium maker. Meanwhile, the USA’s nuclear industry was busy selling the first generation of much-enlarged versions of Admiral Rickover’s enriched-uranium-fueled, light water cooled/moderated submarine reactor at cost so that it could then profit by servicing (fueling) them thereafter. Although several large LMFBRs were subsequently built and operated in France and USSR/Russia, that concept never gained much traction with utility owners because they already had something that met their needs (LWRs) and didn’t want to deal with the problems revealed by the operational history of existing LMFBRs (e.g., persistent sodium leaks/fires - Mahaffey 2014) or assume the greater costs of both the reactors themselves and the fuel recycling systems required for sustainable operation.

79 ORNL’s MSR/MSBR program cancellation in 1973 was accompanied by the “downsizing” of its longtime Director, Alvin Weinberg. The rationale for those actions was that, “the USA could no longer afford to support two breeder reactor programs”. In 1972 Argonne’s LMFBR development work had cost US taxpayers 26 times as much ($123.2M/$4.8M) as had ORNL’s MSBR studies - see Linda Cohen’s, “The Technology Pork Barrel”, Brookings Institution Press, 1991, p. 234.
“sodium cooled reactors are expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair”

Hyman Rickover 1957

The main reason why genuinely sustainable nuclear fuel cycles still don’t get much attention in the USA is that most of its current political leaders consider nuclear power to be just a stopgap while, with the “temporary” help of fracked natural gas, it “transitions” to an imaginary clean/green world powered by conservation, biofuels, magically modified dams, wind turbines and solar panels/towers (plus some super batteries?) linked together with a zero-loss, world-wide magic electrical grid (Jacobson 2009, Jacobson 2017). Consequently, the US government’s nuclear scientists/engineers have been helping their “industrial partners” render today’s unsustainable nuclear fuel cycle more attractive for temporary niche-filling by championing “small modular” versions of their current reactors even though many of those experts understand that such systems don’t represent a stand-alone solution to mankind’s future energy conundrum81.

Another reason why the development of a genuinely sustainable nuclear renaissance still gets short shrift is that doing so is impossible without

81 Here’s the ABSTRACT of a recent critique of that policy: “Small modular reactors (SMRs) have been proposed as a possible way to address the social problems confronting nuclear power, including poor economics, the possibility of catastrophic accidents, radioactive waste production, and linkage to nuclear weapon proliferation. Several SMR designs, with diverse technical characteristics, are being developed around the world and are promoted as addressing one or more of these problems. This paper examines the basic features of different kinds of SMRs and why the technical characteristics of SMRs do not allow them to solve simultaneously all four of the problems identified with nuclear power today. It shows that the leading SMR designs under development involve choices and trade-offs between desired features. Focusing on a single challenge, for example cost reduction, might make other challenges more acute. The paper then briefly discusses other cultural and political factors that contribute to the widespread enthusiasm for these reactors, despite technical and historical reasons to doubt that the promises offered by SMR technology advocates will be actually realized”. (Ramana & Mian 2014).
first performing the “hot”, hands-on research (not just paper studies) required to develop anything capable of addressing the future’s energy/economic/environmental issues. 750–900 kg of fission products would be generated within any fast MSR’s fuel salt per GW_e year, all of which would have to be properly dealt with to prevent possible corrosion damage. Similarly, the wall/walls of the reactor’s core would experience very high neutron bombardment rates that might also cause damage. Answers to the questions raised by these facts will not be obtained until realistic tests are done under realistic conditions. Because the USA’s national laboratories chose to downsize their “hot” experimental facilities/capabilities and replace them with modeling/modelers, it’s become extremely difficult/expensive to perform such work – most NE-related “research” funding is currently spent upon shiny new office buildings and personnel-related overhead.

The choice of which sort of MSR to develop/build/use will ultimately depend upon those characteristics deemed most important to the future’s decision makers. For instance, if it’s still absolutely verboten to have uranium enriched beyond 20% anywhere within a power reactor at any time, they would have to be much bigger (contain more uranium) than would be the case if higher enrichments are allowed. Similarly, if there can’t be any sort of genuinely “bomb grade” fissile anywhere within the

82 Redox control is necessary because fission of an actinide atom randomly generates a variety of two-atom fission product atom pairs which may or may not possess the same net stable oxidation state as the actinide itself. For instance, if the fission of a U+4 atom (atomic number 92) happens to generate a cesium atom (atomic number = 55) and rubidium atom (atomic number 92-55=37) both of which are stable only in their +1 oxidation state, the difference between their before/after net oxidation state (4-2) will cause two of the anions originally accompanying that uranium atom (in this example that’s fluoride) to give up two electrons in order to maintain overall electrical neutrality. That would convert harmless, non-reactive, fluoride anions into one of the world’s strongest oxidants (fluorine atoms) & therefore most corrosive species. A salt-soluble redox buffering agent (e.g., U^{+3} or Zr^{+2}) would scavenge up those fluorine atoms producing non-corrosive fluoride salts (UF_4 or ZrF_4).
system, reactor cores will have to bigger and require more fissile to compensate for the fact that they cannot be surrounded by a blanket. If more or less continuous salt-seeking fission product removal (steady state operation) is considered either too troublesome or too potentially “proliferative”, it could be put off for long periods by, again, increasing both the size of the reactors and the amount of startup fissile in them (breed and burn). Unfortunately, because startup fissile limits the rate at which a sustainable nuclear renaissance could be implemented, all of these alternatives amount to kicking the same can further on down the road.

Finally, and most important, successful implementation of any of the sustainable concepts mentioned above would satisfy 100% of Mankind’s power needs “forever” with abundant and readily accessible natural actinide fuel – not just the 0.71% of natural uranium ($^{235}$U) fissionable in today’s moderated reactors. That would render clean/green nuclear power as “renewable” as is sunlight as well as a heck of a lot cheaper, less environmentally impactful, and more reliable (Cohen 1983). For example, assuming 50% heat to electricity conversion (molten salt reactors run much hotter than do LWRs and would therefore generate roughly 50% more electricity per heat joule (GOOGLE “Carnot efficiency”), just the U within the topmost kilometer of the Earth’s continents (i.e., 2.8 ppm of 4.2E+17 tonnes $\approx$ 1.2E+12 t U), could continuously generate 22 TW$_e$ for 74 million years. Since the earth’s crust contains 3 - 4 times as much thorium as it does uranium, let’s say a total between them of 12 ppm, breeder reactors could potentially

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83 The fresh fissile created in blankets containing fertile isotopes.

84 In reality only a fraction (typically 5/7) of the $^{235}$U in NU is usually recovered during enrichment because it’s cheaper to do so. However, in situ breeding of $^{239}$Pu generally generates enough new fissile to compensate for that loss which is why state of the art LWRs require the mining of “only” about 160 tonnes of NU/GWe year.
generate \( \sim 2.7 \times 10^{12} \) J’s worth of heat energy from one cubic meter of average crustal rock – about 56 times more than that provided by an equal volume of pure “banked” (in situ, not chunked) bituminous coal.

Anyone who feels that such mining would be too environmentally impactful should ponder the following realities:

- The USA’s mountaintop-removal approach to coal mining
- The fracking of the relatively “easy” (shallow) 1.6 to 3.2 km-deep shale deposits (Lallanilla 2018) currently being mined for both oil and gas, causes lots of mini earthquakes, occasionally pollutes ground water, and usually leaks some of its GHG product directly into the atmosphere
- The ~100 ppm U in any shale so mined represents about 4000 times more clean energy as does its ~ 5% oil/methane/kerogen’s dirty energy. This means that 4000 times less rock would have to be so disturbed if the right rock fraction were to be “burned” to produce energy
- Huge amounts of phosphate rock containing a similar percentage of uranium have already being mined and processed – the resulting waste piles are already on the surface of the earth and therefore easily accessed.
- Brazil’s much heralded recent offshore oil discoveries are even deeper and covered with both seawater and rock (Presalt 2018).
- Nuclear power is far less damaging to both the environment and people than is the coal industry (Kharecha, P.A., and J.E. Hansen, 2013)
- The amount of mining required to fuel a breeder reactor-powered world would be much less than required to access the materials required to build a nominally equally(?) capable, clean/green and politically correct (non-nuclear) energy system
- Solar and wind power emits considerably more radiation per kWh than does nuclear power due to the mining/processing (mostly in China) of the rare earths going into them (UNSCER 2016)
According to the U.S. Fish and Wildlife Service, California’s Ivanpah “concentrated solar power” (CSP) solar tower-type power plant\(^\text{85}\) kills approximately 28,000 birds each year when they instinctively try to perch/land upon its highest points – the tops of the towers at which its ~350,000 huge mirrors are focused.

One of the Ivanpah CSP’s selling points was that it is purportedly able to provide electricity when the sun isn’t shining because when it does shine, its molten salts can be heated to 1,000 degrees F and stored in heavily insulated heat energy “batteries” (tanks). However, since sunlight provides only about 23% of that facility’s rated 392 MWe capacity, the rest is provided by burning natural gas both there and elsewhere which dumps about 560,000 tonnes of CO\(_2\) per year into the atmosphere. Like windmill-type “capacity”, CSPs are big natural gas consumers due to their low efficiencies plus the need to “heat things up” with gas every day before sunrise (if the molten salts were to freeze they could damage its plumbing). And also, since 2013, Ivanpah’s owners have twice sought permission to use even more gas than was allowed under the plant’s certification agreement – 1.4 billion cubic feet in 2016 (Martin 2016*). Not surprisingly, solar investment in Spain has dropped by 90 percent from its 2011 level, and worldwide interest in CSP is falling fast.

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\(^{85}\) Ivanpaugh was built with the fervent support of the Sierra Club for $2.2 billion including a $1.6 billion federal loan guarantee. Just its build, not its build+maintenance+profit margin, solar energy cost averaged over 20 years works out to 13.9cents/kWh – 4-5 times that of today’s nuclear reactors.
Windmills also kill millions of birds (especially eagles - GOOGLE it) and bats because the tips of their giant propellers move much faster than they can fly.

Chapter 6. Economics: The main reason that the USA’s nuclear power industry is now on the ropes

Due to Asia’s recent rapid economic development, Mankind’s total energy consumption grew by 50% during the last 20 years and our appetite for still more continues to grow. However, how that appetite is to be satisfied remains as much of a question now as was at the dawn of the nuclear age seventy years ago. We’re just as aware of the finiteness of fossil fuels as we were then, but there are now almost 3 times as many people to feed, and some of humanity’s “technical nerds” are beginning to notice that many of the promises made by the folks selling us windmills, biofuels, and solar energy aren’t likely to come true. Daniel Yergin’s book, “THE QUEST: Energy, Security, and the Remaking of the Modern World” (Yergin 2011), does a fine job of explaining why the tsunami damage to an improperly sited Japanese nuclear power plant caused Germany and several other European powers to declare a moratorium on new plants. Even France, the world’s largest
exporter of electricity generated by nuclear power, voiced some misgivings about it circa 2014.\(^\text{86}\)

Germany which has decided to phase out nuclear power entirely invested $580 billion in renewables and, with the help of its neighbors (primarily Sweden, Norway and France), has achieved 38\% green energy. However, its electricity prices are now Europe’s highest while its carbon emissions have remained flat due to the fact that it had to burn more coal and imported (mostly from Russia) natural gas to make up for its loss of nuclear capacity. Similarly, the state of Vermont shut down its only nuclear reactor in 2014 and switched to gas which raised its per capita GHG emissions by about 5\% during a time when overall US emissions declined by 17\% due to electrical utilities switching from coal to natural gas fired power plants.

Almost a decade ago President Obama said, “To meet our growing energy needs and prevent the worst consequences of climate change, we’ll need to increase our supply of nuclear power. It’s that simple. This one plant, for example, will cut carbon pollution by 16 million tons each year when compared to a similar coal plant. That’s like taking 3.5 million cars off the road.... On the other side, there are those who have long advocated for nuclear power—including many Republicans—who must recognize that we’re not going to achieve a big boost in nuclear

\(^{86}\) However, those misgivings have evaporated since Germany’s recent admission that it will have to buy even more “outside” power as it shuts down more of its nuclear (100\% of them by 2022?) and coal-fired power plants – consequently, the future for nuclear power in France remains bright.
capacity unless we also create a system of incentives that renders all forms of clean energy profitable. That’s not just my personal conclusion; it’s the conclusion of many in the energy industry itself, including CEOs of the nation’s largest utility companies”. (Obama 2010)

President Obama was referring to an $8.3 billion federal loan guarantee for two (numbers 3&4 –that site already has 2 older reactors) new Westinghouse 1.17 GWe AP-1000 LWRs which were to be built at Plant Vogtle, Burke GA (projected 2500 temporary jobs during the build then 800 permanent). Environmental groups opposed to the licensing of reactors filed a petition in April 2011 (after a good portion of that money had already been spent) asking the Nuclear Regulatory Commission's commission to suspend the licensing process until more was known about the Fukushima nuclear accident. In February 2012, nine environmental groups filed a collective challenge to its design certification and a month later filed a challenge to the license that the Nuclear Regulatory Commission (NRC) had issued. In May 2013, the U.S. Court of Appeals ruled in favor of the NRC. By 24 Sep 18 that project’s projected cost had ballooned to $27 billion resulting in its being dropped completely – the affected utilities simply couldn’t afford to keep fighting an uphill battle.

Vogtle’s number 3&4’s fate demonstrates how costs can quickly escalate when cost drivers are poorly managed and/or the lack of a readied supply chain, excessive litigation, slow regulatory interactions, excessive regulator billing rates, etc., become prohibitively burdensome.

Western-leaning countries’ increasing politicization of the relevant rules and regulations combined with large “renewable energy” subsidies, has rendered nuclear power a poor investment and thereby crippled it
Between 2013 and 2018, seven US existing nuclear power plants were permanently shuttered, and 12 others are scheduled for closure through the mid-2020s. The USA is shutting down already-paid-for and well-functioning reactors because their owners can’t make money in its now mostly “privatized” electricity markets. Journalists typically translate that fact to the much more attention-grabbing, “nuclear plants cannot compete” which, again, happens to be misleading. On a cost per kilowatt-hour of energy delivered to the grid, today’s nuclear plants are consistently among the least costly sources available, just above already paid for hydroelectric dams. According to a paper entitled “Nuclear costs in context” (NEI 2017), the average total generating cost for a US nuclear power plant during 2016 was under $0.034 per kWh, 15% lower than 2012’s peak average when Japan’s leadership’s Fukushima-inspired “decapitated chicken frenzy” had already added additional overhead costs to nuclear power generation here too.

87 In most of the world hydropower is already “maxed out” because most of the good locations for big, powerful, dams are already so-used and Mother Nature only provides so much water to fill their reservoirs.
Figure 17: Renewable energy subsidies

Renewable energy is defined in a transparently illogical fashion so as to favor solar and wind. The ostensible motive for increasing renewable energy is to lower carbon dioxide ($CO_2$) emissions thusly avoiding (or mitigating) a global warming catastrophe, but nuclear power can’t be counted to meet those quotas, even though it doesn’t emit $CO_2$. The USA’s solar energy industry is currently telling its Congressional supporters that it’s finally become willing to lose some of its subsidies. The current federal subsidy for solar is 30% of construction cost plus an additional 10% due to especially rapid depreciation for solar plants. The 30% subsidy is now scheduled to ramp down to 10% by 2022 and remain there indefinitely. It’s not a consequence of declining real costs because it has become a mature industry which means that further such declines will be moderate. The real reason is that its leadership knows
that investment tax credits (ITCs) aren’t their most important subsidy. Their real gold mine is the renewable portfolio requirements adopted by many states dictating that a certain percentage of electricity be produced by what they’re selling. Moreover, this country’s technically clueless green new dealers will likely ramp those requirements upwards over time creating a chain of events guaranteeing profits for its solar and wind energy entrepreneurs for decades to come. If that weren’t enough, those industries’ champions are also trying to freeze such quotas into state constitutions to make it difficult for electricity consumers to escape the trap that’s being set for them\textsuperscript{88}.

The world’s existing nuclear plants were designed and built back when electric utility companies constituted legal monopolies with both an obligation to serve and prices established via a government-approved cost-plus rate of return. In that respect they were much like the “socialized medicine” systems currently serving most of the EU’s citizenry. When they were built, no one considered a “what if” in which the USA’s electricity supply business would be deregulated and more politically correct and therefore heavily subsidized new competitors might be able to give away their electricity in order to capture additional market share when Mother Nature was cooperating with them – today’s situation. This of course means that nuclear power “can’t compete” in so-privatized electricity markets during such times. I also suspect that no one back in the good old days ever considered a “what if” in which nuclear power would not receive a tangible (monetary) ”carbon credit”

\textsuperscript{88} This paragraph is a 250 word rewrite of Norman Roger’s essay (Appendix XVII), https://www.americanthinker.com/articles/2019/07/disentangling_the_renewable_energy_scam.html.
for being green with respect to GHG emissions. In 2016 an analysis performed by the Brattle Group concluded that granting zero-emission credits to nuclear power could secure its economic viability in competition with subsidized renewables and low-cost gas-fired plants. It said: "A typical revenue deficit for a vulnerable nuclear power plant is around $10/MWh," which is equivalent to costing "the avoided CO₂ emissions... between $12 and $20 per ton of CO₂, varying with the regional fossil fuel mix that would substitute for the plant”.

Figure 18: California’s ‘duck curve’ (Forsberg 2016)

Figure 18 depicts California’s “dispatchable“ power requirement vs time of day during the decade while its citizens were installing a tremendous number of solar panels. Note the following:

- Historically (pre solar) California’s total power demand during a typical spring day varied about 25% (from about 18 GWe to 24
GWe) ~ 80% of which was provided by thermal (nuclear and fossil fueled) power plants

- As more and more solar panels were added to the system, the total amount of dispatchable energy (but not “capacity”) required was somewhat reduced
- However, more, not fewer, dispatchable power plants had to be built/used because demand maxes out just as the sun is going down in the evening
- Dispatchable power plants still have to supply 100% of demand for about two thirds of each day, especially when it’s cloudy
- They must also be able to respond very quickly to take up that load when the sun goes down or clouds roll in; i.e., respond much more quickly than did California’s “old” power system. In order to respond quickly, backup gas burners are never really off, but kept warm, burning gas, in “backdown mode” (it’s expensive and damaging to start a ‘peaker’ turbine quickly from cold).

Not depicted in this figure is the fact that California’s deregulated wholesale electricity spot prices often go negative at the bottom of a sunny day’s “duck curve”, typically at about 1 PM.

When lots of solar capacity is added to a market, the spot price of electricity will drop precipitously near the middle of a clear day when there is high solar input. The incremental cost of solar production then is about zero and producers receiving subsidies proportional to production will bid electricity prices down to negative values as long as their subsidies exceed them in order to continue sales. The same thing happens on windy days when there’s lots of highly subsidized wind turbine power.

In order to address such situations, NE Professors Charles Forsberg (MIT) and Per Peterson (UC Berkeley) devised an especially clever
concept\textsuperscript{89} featuring a big conventional (air Brayton) gas turbine

![Diagram of Air Brayton Combined cycle molten salt cooled reactor](image)

**Figure 19: Air Brayton Combined cycle molten salt cooled reactor**

that receives its raw heat energy input from any combination of …

- Heat in the air going into the turbine added to outside air by passing it through a massive, well insulated “FIrebrick Resistance-heated Energy Storage” (FIRES) heat energy storage system.
- Heat exchange to either that or “outside” air from heat energy generated by a ~700°C, 236 MWt, fluoride salt–cooled, high-temperature nuclear reactor (“FHR”)
- Additional “peaker” heat generated by adding/burning natural gas to that air

In baseload configuration, no gas is burned and the turbine runs at ~670°C producing ~100 MWe with 100% nuclear power (42% thermal

\textsuperscript{89} I highly recommend reading their open access paper because it is very well written and demonstrates that the USA’s best and brightest are still capable of devising a solution to almost any technical problem posed by its business models. However, since it would be almost impossible to render a solid-fueled, graphite moderated, FHR genuinely sustainable, its development should have lower priority than that devoted to the more promising concepts described earlier in this chapter.
to electric efficiency). When demand rises, gas would be added/burned to raise the turbine’s air’s temperature up to ~1065°C at which point its output would reach its maximum rating, 242 MWe. Finally, when power demand fell below 100 MWe, the difference between it and 100 MWe would go to heat its FIRES “battery” via resistance-type heating elements. Gas burned during its peaking mode would exhibit a heat-to-electricity production efficiency of 66% which is about 10% higher than that of a stand-alone combined cycle gas fired power plant.

The reactor itself would be superficially much like a pebble bed-type HTGR in that its fuel could consist of golf ball-sized graphite spheres containing tiny TRISO kernels slowly circulated through the coolant (molten salt) pumped through its core. Unfortunately, although molten salt cooled reactors do possess some of the virtues of true MSRs, they also possess the rather special drawbacks inherent to TRISO/HTGR-type fuels; i.e., would be uniquely difficult to implement any sort of sustainable fuel cycle with because reprocessing would be so difficult.

Most of today’s solid fueled nuclear reactors could and do vary their output (load follow) at the rate that the western world’s total electricity demand changes but operate more reliably and efficiently when run steadily at their full-rated power. If they are forced to drastically reduce their output in response to today’s (not the past’s) deregulated “market

90 A “combined cycle” gas fired power plant directs the hot gasses coming out of its gas turbine through a tube-in-shell boiler to generate steam that powers a close-coupled steam turbine. They are considerably more fuel efficient than “peaker plants” but cost more and can’t load follow nearly as well.

91 For example, their core could/would be much more compact than a HTGR’s because its working fluid/coolant, FLiBe, is a better coolant than is any gas.
forces” and remain in that state too long, a short-lived gaseous neutron absorbing isotope (“poison”), xenon-135, builds up inside their hermetically sealed solid fuel rods which shuts them completely down for a day or so. Molten salt reactors would be better load followers because all gaseous fission products would be continuously sparged (removed) from their fuel and therefore couldn’t accumulate.

Being shut down and unable to generate power during market-driven demand transients is more detrimental to a LWR’s revenue generation than is simply accepting low or negative pricing whenever the sun happens to be bright and/or the winds especially strong.

In spite of this, during 2017, the USA’s ~100 nuclear power plants with a rated generating capacity well under 10% of its total, supplied almost 20% of the electricity actually produced and sold. The average capacity factor of its plants exceeded 92% and the total electrical energy generated/sold was ~800 billion kilowatt-hours. However, their owners continued to lose money, which is certainly not a “sustainable” situation as far as they are concerned – that’s why they are responding by shutting down already paid for reactors. Of course, this means that their output has to be replaced with inefficient, natural gas-fired, “peaker plants” that dump lots of CO₂ into the atmosphere whenever Mother Nature isn’t cooperating with our renewable energy entrepreneurs⁹². That’s perfectly OK with Mr. Trump and his enablers because, to most of them, coal is “clean”, fracked natural gas and oil will last forever, and global warming

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⁹² “Cheap” peaker plants are fuel inefficient because, 1) they must be kept running (idling) at zero load when wind/solar is able to satisfy power demand and, 2) their exhaust gases don’t heat boilers driving additional turbo generators.
is just another hoax perpetrated by Democrats, socialists, tree huggers, and foreigners.

Contrary to commonly held/expressed opinions, nuclear power is not nearly as heavily subsidized\(^{93}\) as are either today’s favored renewable energy sources or fossil fuels. On March 13, 2013, Terry M. Dinan, senior advisor at the Congressional Budget Office, testified that federal (not the total) energy related expenditure for that fiscal year were follows: Renewable energy: $7.3 billion (45 percent)  Energy efficiency: $4.8 billion (29 percent)  Fossil fuels: $3.2 billion (20 percent)  Nuclear energy: $1.1 billion (7 percent). In addition, he testified that the U.S. Department of Energy would spend an additional $3.4 billion on “financial Support for energy technologies and energy efficiency” as follows: Energy efficiency and renewable energy: $1.7 billion (51 percent)  Nuclear energy: $0.7 billion (22 percent)  Fossil energy research & development: $0.5 billion (15 percent)  Advanced Research Projects Agency—Energy: $0.3 billion (8 percent)  Electricity delivery and energy reliability: $0.1 billion (4 percent). That situation has apparently gotten worse: Wikipedia’s current entry for “Energy subsidies” (Energy subsidies 2018 [https://en.wikipedia.org/wiki/Energy_subsidies](https://en.wikipedia.org/wiki/Energy_subsidies)) includes the following:

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\(^{93}\) With investment subsidies, the financial burden falls upon the taxpayer, while with feed-in tariffs the extra cost is distributed across the utilities' customer base thereby raising everyone’s power bills. While investment subsidies may be simpler to administer, feed-in tariffs reward actual production/sales. Investment subsidies are paid out as a function of the nameplate capacity of the as-installed system and are independent of its actual energy yield over time and thereby reward both overstatement of power rating and toleration of poor durability and maintenance. Some electric companies offer rebates to their customers, such as $2.50/watt of “capacity” installed up to $15,000.
figures: Foreign tax credit ($15.3 billion) Credit for production of non-conventional fuels ($14.1 billion) Oil and Gas exploration and development expense ($7.1 billion). The three largest renewable fuel subsidies were: Alcohol Credit for Fuel Excise Tax ($11.6 billion), Renewable Electricity Production Credit ($5.2 billion), and Corn-Based Ethanol ($5.0 billion).

If you go through those numbers adding up everything having to do with rewarding entrepreneurship in renewable, nuclear, and fossil fuel electrical energy generation and then divide by how much energy each actually delivers to its customers (15% for renewables, 20% nuclear, and 65% fossil fuels), you’ll see that nuclear power

![Electricity prices in California rose 5x more than in rest of U.S.](image)

Figure 20: California’s “special” electricity costs (volunteered by Alex Canarra)

receives about 30% as much of the government’s “help”/kWh as do the fossil fuel industries and ~1.8% that given to the people being encouraged to sell us windmills, solar panels/towers, biofuels, etc.. This sort of governmental activism has caused electricity prices to spike
wherever it is most prevalent (for example, California, see Fig 17) and also increases GHG emissions because it encourages utilities to substitute natural gas for uranium 94.

Due to the demand perturbations when additional intermittent renewable electricity is added, standard marginal cost-based pricing approaches tend to generate wholesale electricity prices that are too low for baseload-capable natural gas, coal, and nuclear power providers. Wholesale electricity rates that support baseload capacity tend to diverge further and further from those required to keep them viable as more intermittent power is added to the mix. However, Figure 21’s dotted line illustrates that wholesale electricity prices (spot prices) fell throughout Europe, as retail residential electricity prices increased in lockstep with increased intermittent supply. What’s particularly interesting is the fact that in 2016, wind & solar generated 8.3% and 3% of Europe’s electricity respectively (Tverberg 2019). This means that what retail consumers have to pay for electricity goes up radically - note what happened in Spain (mostly due to its commitment to solar development) and Germany (mostly due to its devotion to wind power) - when even a relatively small fraction of the total power consumed is produced with intermittent sources.

94 According to the dictionary, renewable electricity is generated by a source that is either naturally replenished or inexhaustible. The state of California’s definition of renewable differs in that it is a compilation of green dogmas (a 112-page RPS Eligibility Guidebook, Ninth Edition Revised, details California’s definition of renewable electricity (CAdotgov 2109)). Fossil fuels are taboo. Although hydro electricity is naturally replenished by the rain, to California’s rule makers, it is renewable only if it does not interfere with kayaking and fish. California loves wind and sunlight for generating electricity. Because anti-nuke hysteria trumps global warming hysteria, carbon-free nuclear electricity generated by breeder reactors would not officially be renewable.
Despite the fact that the consequences of their decisions have been repeatedly pointed out to both US and EU policy/decision makers and they usually respond by announcing intent to address them, their/our governments’ (state, federal, and sometimes even city) continue to subsidize/support companies installing/operating weather-dependent power sources in areas already subject to frequent periods of over supply when the weather is “right”. Though those subsidies are repeatedly scheduled to expire, they are also repeatedly granted last minute extensions which “rescues” are likely to continue due to lobbying. Alternative energy companies have become especially politically correct “big businesses” with well-heeled owners who employ lots of people
and are especially generous contributors to reelection campaigns (see APPENDIX XVII). In this respect, solar and wind power are much like the USA’s deeply entrenched, but energetically and environmentally nonsensical, corn and soybean-based biofuel programs (SciAm 2014).

“...on wind energy, we get a tax credit if we build a lot of wind farms. That’s the only reason to build them. They don’t make sense without the tax credit.” (Buffet 1014)

The main problem with today’s renewable energy sources is not their headline cost per kWh, but that they’re a bad match to a demand-driven energy system. ~80% or so of US energy use (after conversions) is non-electric. With the exception of today’s already nearly maxed out hydroelectric dams, renewables are non-dispatchable electric.

In response to government mandated increases in the proportion of power subject to the whims of Mother Nature (wind and solar), several US utilities are installing megawatt-scale battery systems to mitigate the resulting fluctuations. Utilities in Hawaii, California, and Arizona (APS) have been early adopters and have installed a number of giant lithium ion battery-based “Powerwall’s” in regions with lots of solar panels.

An April 2018 fire and explosion at a relatively tiny (2 MW) battery facility west of Phoenix AZ highlighted the challenges posed by a battery backed-up wind/solar based power grid. That particular explosion sent eight firefighters and a police officer to the hospital. The root cause of that and other such incidents both large and small (in airplanes, cars, cell phones, etc.), is that upon recharge the lithium within such batteries tends to form metallic dendrites that penetrate the electrolyte separating their electrodes and short them out. The resulting heat spike ruptures the battery case and its metallic lithium and
flammable electrolyte (an organo carbonate) quickly ignite & go up in a smoke.

Today’s electricity storage systems can’t render today’s intermittent wind and solar energy sources practical. A recent analysis of grid-scale US “unsubsidized and levelized electricity storage” costs (Lazard 2017) for various sorts of storage systems concluded that if lithium ion batteries were to replace today’s gas-fired “peaker plants” the overall system’s Levelized Costs of Storage (LCOS)\(^95\) would be about $282/MWh\(^96\). To put this number into perspective, let’s do another calculation: GOOGLEing reveals that the average US household consumes 10.4 MWh per year of electricity costing (retail) about 12 cents per KWh—a total of $1282/a. If 100% of that power were to be produced with wind turbines and solar panels possessing capacity factors of ~30% and 15% respectively, it seems pretty likely that at least half of the power going into the average US home would be coming from some sort of storage system – not directly from such unreliable sources. If that proportion happens to be 50%, with lithium ion battery-based storage that home’s annual power bill would increase $1644 \([50/100*10.4*282]\) meaning that electricity would now be costing its residents over 26 cents/kWh. The average US wholesale cost of nuclear power is currently about $0.03/kWh.

\(^95\) LCOS = sum of all costs per year / MWh stored/discharged per year

\(^96\) Today’s cheapest mass storage option - mass compressed air storage in underground salt caverns - is terribly inefficient. Only about 27% of the energy required to pump air into such caverns is recovered because its heat of compression is lost to the surrounding salt. Consequently that air must be reheated – usually be adding/burning natural gas.

https://en.wikipedia.org/wiki/Compressed_air_energy_storage,
As is the case with LWRs, for that application, lithium ion batteries represent a prematurely locked-in technology poorly suited to the problem that it is now supposed to address. However, there are several more promising alternatives. For example, liquid metal batteries can’t fail the way that lithium ion batteries do and are also apt to be much cheaper because they feature liquid (molten) - not solid, cheap - not expensive, metallic electrodes separated by a molten salt electrolyte. Their operation relies upon density/SPG differences: a high density (e.g., antimony) metal electrode lies on the bottom of the cell. Immediately above it is an intermediate density molten electrolyte (e.g., a low melting mix of lithium and potassium chloride salts), and a low density liquid metal (e.g. lithium) electrode floats on top. Like oil & vinegar those fluids naturally self-segregate and charging/discharging them doesn’t generate the sorts of irreversible physical changes that eventually cause any solid electrode-based battery system to fail (lithium ion batteries are unlikely to last more than ten years in such applications). Professor Donald Sadoway’s group at MIT has looked into a plurality of cheap metal (e.g. sodium, calcium, magnesium…) battery chemistries. What makes this sort of battery especially promising is that unlike any of the competing solid electrode based systems, examples have retained >99 percent of their initial capacity after over five thousand, 100% charge/discharge cycles – a characteristic absolutely necessary for a genuinely practical, grid-relevant sized (>>1 MWh) electricity storage system. Professor Sadoway estimates that his batteries will eventually cost about $75/KWh, which, if they last for 20 years, @ one charge/discharge cycle per day, corresponds to a LCOS of just $10.3/MWh [$75/20/(365 cycles/year*0.001 MWh/cycle).

Unfortunately, enough of even such cheap batteries to store one day's worth of 22 TWe power (approximate world demand circa 2100 AD) would cost ~39.6 trillion of today’s US dollars.
Edisons’~120 year-old nickel-iron (Ni Fe) battery has proven to be the most durable (by far) solid electrode storage battery. It’s extremely robust, tolerant of abuse, (overcharge, overdischarge, and short-circuiting) and often exhibits very long life even if so treated. However, due to its low specific energy/power (energy/power per kilogram), relatively poor charge retention, and high cost of manufacture (retail cost per kWh is currently about 60% higher than a TESLA Powerwall), other types of rechargeable batteries have largely displaced them. However, it’s experiencing a resurgence in some quarters (as the “Battolyser”-GOOGLE it) because overcharging them generates hydrogen which can be stored and used for a host of purposes including energy generation via either combustion or in fuel cells. In that manner, they could accomplish both short-term and long-term energy storage. However, even if they were to last for 30 years, their relatively high up-front cost (currently about $83) translates to a LCOS of $76/MWh.

Upon first glance, some renewable energy technologies currently have energy returns on investment (EROI) higher than that of an equivalent fossil (e.g. new coal) fueled or nuclear power plant. However fossil energy provides the energy required to do the mining, extraction, transporting, building, etc. required to install any sort of politically correct renewable energy source

“Solar panels are ‘rebuildable’, not ‘renewable’” (Berman 2017).

It will take a long time to progress away from today’s chaotic “all of the above” approach to supplying electricity and even longer to generate enough of it to meet the needs of a considerably bigger, richer, and fairer future. Over the long haul, the biggest issue facing our descendants will be the unsustainable debt load that we have left them. The USA’s external debt - total public and private debt owed to nonresidents repayable in internationally accepted currencies, goods or services – is
currently much higher than than any other nation, about 20 trillion dollars or $59,000 per capita. China’s external total public and private debt is now about 1.8 trillion or ~$1300 per capita. The USA’s debt to GDP ratio is now 1.05 - China’s is 0.48.

The difference between a country's external financial assets and liabilities is its net international investment position (NIIP). A positive NIIP indicates that the nation is a creditor, while a negative value indicates that it is a debtor. The USA, as recently as 1960 the world's largest creditor, has now become the world's largest debtor. With the recent rapid ascent of Hong Kong Monetary Authority's credit position, China (including Hong Kong and Macau) has recently been jousting with Japan for the top creditor position.

The fact that Hubbert was absolutely right97 about how long fossil fuels are apt to remain cheap enough to burn combined with the magnitude of the world’s debt overhang means that any “green new deal” must be implemented with cost efficient, practical technologies – not with those with especially fine-sounding names, eminently politically correct, and/or immediately profitable for well-connected established businesses, entrepreneurs, or investors.

There’s currently a good deal of unrealistic propaganda about how tight shale gas and oil could meet our energy needs “for the foreseeable

97 Professor Hubbert clearly defined the assumptions behind his conclusion (see Fig 3) that fossil fuels could not indefinitely power a technological civilization. Since circa 1970, the fossil fuel industry’s champions have repeatedly cherry-picked/changed those assumptions (e.g., how “tight” the oil in question might be) and time scales to” prove” that he was wrong. Since most people would prefer a comfortable/soothing lie to an uncomfortable truth, those champions have done a pretty job of convincing the rest of us that we don’t have anything to worry about.
future”. If “foreseeable” means one election cycle or another decade or so, that’s reasonable – if it means one average current human lifetime, its patent nonsense. Claims that society can seamlessly move from fossil to politically correct renewable energy without drastic changes in consumption habits and lifestyles are equally misleading. Most things we’re told that sound too good to be true are untrue regardless of their source or possibly constructive intent.

What all this should be telling our decision makers is that it would make sense to develop/build sustainable power plants capable of generating power when it is needed, not just whenever Mother Nature decides to let the wind blow and/or clear away her darkness and clouds.

In conclusion, I recently answered this QUORA question, “How do the economics of wind and nuclear power compare? with…

“This question’s answer depends upon what kind of “economics” you’re talking about. If you’re selling wind mills in a state like California that heavily subsides any sort of politically correct (not nuclear) “clean” power source regardless of how unreliable (intermittent) it is and doesn’t care a hoot about its citizens’ electricity rates, wind power’s economics are really attractive. On the other hand if you’re trying to make America great again by building a factory that requires electricity to make stuff, wind power’s economics really suck because you can’t depend upon being able to actually run it."

6.1 Generic reactor build costs

Another of nuclear power’s problems in Western-world countries is their inflated reactor build costs. The fate of Vogtle 3&4 demonstrates how project costs quickly escalate when their drivers are poorly managed and reflect contextual factors (e.g. lack of a prepared supply chain and
experienced labor force, slow regulatory interaction paces, expensive regulator billing rate, etc.) become intractable burdens. In most engineering fields it is possible to accurately estimate a proposed project’s cost utilizing information in the “economics” sections of tomes like “Perry’s Chemical Engineering Handbook”. However, that doesn’t work with the Western world’s nuclear power projects because even though the facilities themselves aren’t especially unique, the costs of everything including labor going into them are both uniquely and artificially high, often by almost an order of magnitude. It is difficult to come up with reasonably accurate build cost estimates because, like those of the USA’s health care system, there is little correlation between “should” and “actual” due to sometimes unnecessary, usually self-serving, and often litigious overhead costs. The effect of those cost drivers are best illustrated by a figure (Fig. 22) excerpted from a paper compiling historical construction costs of full-sized civilian light water reactors

98 In the USA it’s possible to make a good living doing such things which mean that litigation, regulation, and oversight have become some of the USA’s more lucrative white collar “service industries”. For example, in 2017 each of the USA’s Nuclear Waste Technical Review Board’s 14 FTE (full time equivalent) jobs was funded at $257,000 per annum. Each of the The Defense Nuclear Facility Safety Review Board’s (DNFSB’s) 117 FTE’s cost US taxpayers about $190,000.
Figure 22: Historic worldwide inflation-adjusted reactor build-costs throughout the entire world (Lovering, Yip, and Nordhaus 2016). The USA’s build cost per GWe started out at under $1 billion 2010-dollars in the late 1960’s but quickly ballooned by over an order of magnitude (which eventually killed its nuclear industry) while those of better disciplined countries (Japan, China, France and So Korea) remained at about $2 billion for several decades. Like the cost of real estate, current reactor build costs are determined by “location, location, location” – high in western countries and much lower elsewhere. Consequently, as of 2018, most of the 58 power reactors under construction and 154 planned (220 GWe Total) are in Asia. As of January 2019, another 337 of them have been proposed (World Nuclear 2019)

Over the long haul, any reactor build cost under ~4 $billion/GWe is economically justifiable because its product will surely be worth much more than that. For example, at 3 cents per kWh, the electricity generated by a one GWe reactor over a 40 year lifetime would be worth $10.5 billion [$0.03/kWh*1E+9 J/s*3.15E+7s/year*40 years/3.6E+6 J/kWh].
6.2 Sustainable reactor build costs

In 1970, a paper written by two of ORNL’s senior-most nuclear engineers (Bettis 1970) included an analysis of what power generated by a full-sized molten salt breeder reactor should cost. Their figure included the costs of construction ($0.159 billion 1970 dollars) fueling, and operating a one GWe breeder reactor. Applying the USA’s subsequent ~6.46x inflation factor for most things to their conclusion ($0.0041/kWh) generates a should-cost figure of $0.0265/kWh – about 40% of the USA’s current average wholesale electricity cost. This suggests that if the USA’s ~320 million citizens set out to power themselves at the rate I’ve assumed for the future’s 11.2 billion people (2 kW$_e$ average with a 40% peak) with one GW$_e$ molten salt breeder reactors, building the 857 [30000*0.32/11.2] of them so required should cost about $860 billion of today’s dollars [857 *6.46 *$0.159 B], To put that figure into perspective, it is only about 35% [860/634 =1.35]) more than the USA’s current annual “discretionary” (nominally) military spending (OMB 2017). Similarly, since the USA’s national debt is now ~$22 trillion and the interest rate on its 10 year treasury bonds is ~2.49% (1Apr2019), it seems likely that its taxpayers are paying someone (?) ~$1.5 billion per day just to service their federal government’s debt, not to address the technical issues threatening their children’s futures.

Fast MSRs should be cheaper to build than the graphite moderated LFTR-type reactors that ORNL’s engineers were envisioning circa 1970 because they would be smaller, simpler, and require less fuel cleanup. For instance, their cores could be so small (8-10 m$^3$/GWe) that it should be possible to design them so that components subjected to especially high neutron flux would be cheap/simple to replace. This is an important point because any product’s durability (and affordability) is as much
determined by its maintainability as by its frequency of failure. Maintainability is determined by the difficulty of parts replacement plus their cost. For example, for the MSFR, the key replacement part would be the annular tank containing the blanket salt surrounding its core. The volume of that tank would be about $7 \text{m}^3$ and its surface area about $50 \text{m}^2$ meaning that if it were 1 cm thick and made of 8 g/cc metal, it would weigh roughly 4 tonnes. Real world prices of the “super alloy” it’s apt to be made of is roughly $25/\text{kg}$, meaning that its cost should be about $100,000 or ~10% of just one day’s worth of its $0.03/\text{kWh}$ product.

The secret to making nuclear energy inexpensive has been known ever since France proved that it could be done over 40 years ago. One design is licensed for a generation and then standardized copies built across the grid. South Korea is apparently still able to do so now. In that fashion, all of the logistics plus an experienced construction workforce is ready for every order that comes in. I'm also convinced that THORCON’s “build 'em like ships” philosophy is the right way to do things. However, it should be easier/cheaper to build and ship the “guts” of a MSFR, MCFR, or MOLTEX than an equally powerful graphite-moderated MSR like THORCON because they would be considerably smaller and weigh much less. ORNL's single salt MSBR's core contained about 300 tonnes of graphite (Robertson 1971) and the “almost breed and burn” denatured (more politically correct) MSR concept (“DMSR”) that succeeded it (Engle 1980) contained about 2400 tonnes of graphite. Calling any such system "modular" or "transportable" requires the same sort of faith-based reasoning

99 The loss of logistics capability and an experienced workforce is largely responsible for the western world’s nuclear build-cost overruns.
responsible for the outcome of the 2016 US presidential election. The fragile parts of a FS-MSR or tube-in-shell type reactor core would be much more compact and consist of 2–4 tonnes of a "hard metal" that could be quickly crushed into durable half cubic meter waste forms whenever they were removed/replaced.

Unfortunately, utilities are now leery of building any sort of nuclear plant because they represent long term investments suitable only for a stable (predictable) economic system. The stability required to implement a nuclear powered future would require cooperation at all levels including government leadership able to look beyond the next election cycle, a better educated populace that doesn’t readily succumb to the whims of fear or fashion, and investors that understand that a rising tide should lift all boats, not just theirs. The lower that interest rates for building nuclear reactors become and the longer those investors can feel confident that their money will keep coming back to them, the lower that energy prices can be for everyone. I don’t mean just “competitive with natural gas”, I mean low enough to make every other energy source uneconomical.

If we could build a one GWe breeder/isobreeder for $2.5 billion as can South Korea their much bigger and intrinsically more expensive CANDU reactors with 2% (interest) dollars then its electricity could be sold for $0.024/kWh for 80 years or for $0.068/kWh for 10 years and then $0.0165/kWh for the remaining 70 and still give its investors a 2%

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100 “Thoughts and prayers” don’t solve technical problems. However, I can sympathize with the "deplorables" who apparently concluded that any sort of change would probably be better for them than more of the business-as-usual thinking exemplified by the previous administration's (& Congress’s) "all of the above" energy policy.
annual return. Unfortunately many western societies now can’t seem to do such things because the people who must work together to implement any sort of sustainable nuclear renaissance do not evince the necessary maturity, courage, and foresight. Nuclear isn’t “too expensive” because of its real costs, but because our leaders don’t act like leaders should.

6.2.1 Materials

6.2.1.1 Concrete, steel, etc.$^{101}$

Generating a kWh’s worth of electricity (energy, not “capacity”) with any sort of nuclear reactor requires far less building materials than does doing so with today’s politically correct power sources. (Figure 23)

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$^{101}$ The following example’s numbers are from Chapter 10 of George Erickson’s, “Unintended Consequences: The Lie that killed millions and accelerated climate change”, web version is free at [http://www.tundracub.com/htmls/unintendedconsequences.html](http://www.tundracub.com/htmls/unintendedconsequences.html). A more detailed compilation of build costs for GHG-free electrical energy sources may be found in “Critique of 100% WWS Plan “ (Maloney 2018).
Figure 23: materials requirements for different energy sources

Let’s go through an example assuming that we wish to replace Vermont Yankee’s medium sized (620 MW) 46 year old LWR with 310 MW (average) wind power, 155 MW (average) PV solar power, and 155 MW (average) of Concentrated Solar Power (solar tower/mirror combo).

Building the solar and wind power facilities would require:

~450,000 tons of steel (0.6% of current U.S. total annual production).

~1.4 million tons of concrete (0.2% of US production/a).

The CO₂ emitted in making the wind/solar renewable energy facilities would be about 2.5 million tons.

The cost of building that much wind/solar generation capacity would be about 12 billion dollars.

The land required to build that much wind/solar capacity would be about: 73 square miles (larger than Washington DC)
Here’s a more reasonable suggestion:

Replace Vermont Yankee with a new Westinghouse /Toshiba AP1000 producing 1.1 Ge, almost twice Yankee’s.

When we normalize the AP 1000’s output to Vermont Yankee’s, generating 620 MW’s worth of nuclear reactor power would require…

~5800 tons of steel (about 1 % as much as would the wind and solar alternatives).

~93,000 tons concrete (about 7% as much as would wind and solar)

CO₂ emitted by the processes going into building that reactor [making its concrete and steel] would be ~115,000 tons (~ 5% that required to build an equivalent amount of wind and solar energy generating facilities).

Cost: We won’t know this for sure until the Chinese finish their first-of-a-kind (FOAK) US and French Gen III+ reactors (AP1000 and EPR), but it is likely that so designed/Chinese fabricated LWRs will cost from 3 to 4 $billion/ GWₑ – pretty high but only one third that of this example’s wind/solar alternatives.

Another material resource that’s much more efficiently used and less impacted by nuclear rather than wind and solar energy power plants, is the land itself. For instance, the area covered by the 4.7 GWₑ Fukushima Diachii power plant is about 1.6 km² which, assuming 90% CF, works out to about 2700 watts/m² of the land so utilized

Assuming a capacity factor of 0.3, properly spaced wind turbines generate an average of 0.3 watts/m² of landscape so blighted – about ten thousand times under that utilized by Fukushima Diachii (calculation based upon https://www.theengineer.co.uk/issues/january-2011-online/wind-turbines-need-to-be-farther-apart-suggests-study/ )
Assuming my Nigerian example’s solar panels and my home town’s (Idaho Falls, ID) solar insolation value (1891 kWh/m²), solar panels would generate an average of about 41 watts/m².

Another thing that decision makers should consider is that nuclear power plants are far less apt to be destroyed by the world’s increasingly frequent/severe floods, tornados, and hurricanes than either solar panels or windmills [Link to WeatherJunkies post].

### 6.2.1.2 Other Metals

The future’s molten salt breeder/isobreeder reactors must be made of materials able to retain sufficient physical strength at temperatures up to about 750°C. Those materials must also be sufficiently resistant to high neutron fluxes and the corrosive components of their salt stream(s). A great deal of experimental work performed at ORNL between circa 1955 and 1973-4, suggested that for the fluoride salt-based concepts that it was considering, a molybdenum/nickel/iron/chromium alloy, “Hastelloy N”, would likely work. Subsequent Russian and French work agreed with that conclusion. Providing that the redox state of their salt streams were to be buffered at a highly reducing level with something like Zr²⁺, MCFRs could probably be built of either 316 stainless steel or the austenitic (heat treated) “HT 9” stainless steel that Argonne/INL has concluded would be suitable for its LMFBR’s fuel.

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102 The people designing the THORCON reactor plan to use the five-fold cheaper 316 stainless steel.
assemblies\textsuperscript{103}. Neither metal is particularly difficult to work with nor fabulously expensive (not “unobtanium”).

Let’s do another example:

How often would we have "maintain" our little molten salt test reactor (e.g., see Fig. 26) by replacing its worn-out core tank?

A recent Lawrence Laboratory report addressed radiation damage to steels exposed to high flux fast neutrons within the cores of fast reactors (Caro 2012).

“HT-9 steel is a candidate structural and cladding material for high temperature lead-bismuth cooled fast reactors. In typical advanced fast reactor designs fuel elements will be irradiated for an extended period of time, reaching up to 5-7 years. Significant displacement damage accumulation in the steel is expected (> 200 dpa) when exposed to dpa-rates of 20-30 dpa Fe/y and high fast flux (E > 0.1 MeV) ~4 x 10\textsuperscript{15} n/cm\textsuperscript{2}s. Core temperatures could reach 400-560\textdegree{}C, with coolant temperatures at the inlet as low as 250\textdegree{}C, depending on the reactor design. Mechanical behavior in the presence of an intense fast flux and high dose is a concern. In particular, low temperature operation could be limited by irradiation embrittlement. Creep and corrosion effects in

\textsuperscript{103} Another possibility that I haven’t heard about yet is that it seems that the core “tank” of a MSR would be a natural candidate for “cathodic protection”. Cathodic protection stops the corrosion of a metal’s surface by making it the cathode of an electrochemical cell. One way to do it connects the metal to be protected to a more easily corroded "sacrificial metal" which acts as the anode (sacrificial metal corrodes instead of the protected metal). For other structures an external DC electrical power source provides sufficient current to protect the surface. Investigating ideas like these will require a MSR-type test reactor.
liquid metal coolants could set a limit to the upper operating temperature.”

Note that steel embrittlement (damage) is more important at low temperatures than it would be at temps typical of a molten salt reactor. Note too that like with the sodium cooled fast reactor, the reactor in question subjects that cladding metal to the maximum possible neutron flux because its fuel is contained within tiny steel tubes which pass throughout the entire system. With the exception of MOLTEX’s concept, the steel of a MSR’s core tank is at its periphery well away from its center – typically by at least one meter. This means that the neutrons impinging upon it would both less numerous & not moving as fast.

If for the sake of conservatism we ignore that fact and assume that its steel’s wall flux would be the same as that at the center of a lead cooled fast reactor, we could expect a HT9 core tank to last 200 dpa/20-30 dpa/year or from 6.6 to 10 years before we’d have to shut the reactor down, drain the tank, & then replace it.

If the reactor’s core tank were to be made of the more chemically resistant & higher temperature-rated 316 SS steel or Hastelloy N instead (~100 dpa limit see IAEA 2012), it would have to be replaced about twice that often.

**6.2.1.3 Isotopically pure salts**
The most expensive component of any breeding-capable fluoride salt-based MSR like the LFTR or MSFR, is apt to be the isotopically pure
Li that its fuel and blanket salt streams must be made of:\textsuperscript{104}. Although ORNL produced a half tonne of pure \textsuperscript{7}Li during the early 1960’s to test its “molten salt reactor experiment” (MSRE), the USA no longer possesses the ability to make it:\textsuperscript{105}. However, it’s very likely that suitably motivated entrepreneurs could produce it today for under $300/kg (Ault 2012) which means that all of the \textsuperscript{7}Li within a MSFR would cost about as much as one day’s worth of its product.

Similarly, the most expensive single component of a fast chloride salt, breeding-capable MSR other than its startup fissile would be the isotopically pure \textsuperscript{37}Cl that its salt stream(s) should be made of. No one makes it now because there’s currently no market for it, but, again, it should relatively easy/cheap to produce because the same centrifuges currently enriching uranium, could probably enrich chlorine (in the form of gaseous HCl) more easily/quickly/cheaply than they can uranium:\textsuperscript{106}.  

\textsuperscript{104} Lithium’s other natural isotope, \textsuperscript{6}Li, has a very high neutron absorption coefficient (cross section) which simultaneously “kills” the reactor’s reactivity while its transmutation generates lots of troublesome tritium. Tritium is both exceptionally labile (can penetrate many metals) and is, in principle at least, biologically impactful. Chlorine-35 exhibits a fairly substantial scattering cross section for fast neutrons which would significantly reduce a MCFR’s breeding capability. It also would generate politically incorrect \textsuperscript{36}Cl (which is also, in principle, biologically impactful) along with some \textsuperscript{36}S that might be corrosive.

\textsuperscript{105} ORNL’s “COLEX” lithium isotopic separation process involved electrolysis of aqueous salt solutions with mercury electrodes, which in that first nuclear era’s “relaxed” regulatory environment, resulted in serious ground water and soil pollution. Today that separation would likely be done with either atomic vapor laser isotope separation (AVLIS), a method by which sharply tuned lasers are used to separate isotopes via the selective ionization of metallic vapors, or liquid-liquid extraction with crown ethers.

\textsuperscript{106} the ease of a centrifugal separation is determined by the square root of mass ratios: It’d be easier to separate chlorine isotopes because \[((1+37)/(1+35))^0.5 >> ((6\times19+238)/(6\times19+235))^0.5\]
It would also be easy to recycle because the same process that represents the “best” way to treat/solidify a MCFR or MOLTEX reactor’s waste streams—iron/aluminum phosphate glass vitrification—quantitatively separates chlorine in an easily captured/recycleable form (HCl – see Siemer 2012).

6.2.1.4 Other Materials

Most thorium breeder reactor concepts would require large amounts of fluorine (e.g., the MSFR’s fuel and blanket salts would contain about 33 tonnes of it). Although there’s plenty of cheap and readily available fluorine ”ores” (fluorite), a good source of already-separated fluorine would be that in the roughly 1.2 million tonnes of “depleted” uranium (DU) hexafluoride stored in/around the world’s uranium enrichment facilities. Like the Hanford Site’s reprocessing waste, it is a corrosive liquid currently “temporarily” being stored in steel casks, some of which are leaking. It could be converted to safer-to-store and potentially useful solid UO₂ plus useful/recyclable HF via “steam reforming” with some added hydrogen gas.

6.2.1.5 Startup fissile

Since building a GWₑ’s worth of any sort of breeder reactor other than the aforementioned tube-in-shell concept would require 4 to 15 tonnes of startup of fissile (²³³U, ²³⁵U, and/or ²³⁹Pu), getting enough of it together to start enough of them to power my scenario’s clean/green future constitutes its toughest technical issue.

Before describing a way to address it, I should point out that the current generation (GEN III) of non-breeders also requires about that much fissile/GWe to start up – the difference being that they must be
continuously fed additional fissile derived from additional natural uranium throughout their entire lifetimes.

Appendix V is a simple program like those we were all empowered to write back when personal computer operating systems included a straightforward, customer-programmable, BASIC language¹⁰⁷. I’ve assumed the scenario generally adopted by the world’s nuclear engineering (NE) R&D experts for any sort of fast reactor; that is, they would be started up with fissile “pyroprocessed” from spent LWR reactor fuel (e.g., GNEP) plus that in the world’s “excess” weapons grade \(^{239}\text{Pu}\) and \(^{325}\text{U}\)¹⁰⁸. Since doing that is both technically feasible and serves two politically correct purposes¹⁰⁹, there’s a pretty good chance that it might actually be employed. APPENDIX V’s example program assumes that Mankind continues to do nothing for another five years (pretty safe assumption) while the necessary R&D is being done while \(~400\) GWe’s worth of LWRs continue to operate. Those LWRs operate for another 15 years while new breeder reactors are added at a rate equal to total fissile “pyroprocessed” from spent LWR reactor

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¹⁰⁷ Downloading DOSBOX & figuring out how it works (it’s not too tough) lets you write your own little programs like this one.

¹⁰⁸ The world currently has about 200,000 tonnes of spent fuel in retrievable storage. Assuming that such fuel contains an average of 1.2 wt% Pu 70% of which is fissile \((^{239}\text{Pu}+^{241}\text{Pu})\) that total comes to 1680 tonnes. The USA also purportedly still possesses ~600 tonnes of cold war-generated, weapons grade HEU, (POGO 2014). In addition, the USA’s production reactors generated roughly 100 tonnes of bomb-grade plutonium (>90% \(^{239}\text{Pu}\)), much of which is currently being stored in vaults at DOE’s Savannah River National Laboratory. This adds up to a grand total of 2380 tonnes of startup fissile if our leaders decide to beat their swords into ploughshares.

¹⁰⁹ i.e., it would destroy both weapons grade fissile and “reactor grade” plutonium thereby rendering today’s stockpile of spent fuel “waste” easier/simpler/cheaper to dispose of.
fuel\textsuperscript{110} plus that in the world’s “excess” weapons grade $^{239}$Pu and $^{235}$U divided by the number of tonnes of startup fissile required per reactor divided by 15 (the number of years). After twenty years additional new breeders are added with fissile ($^{235}$U) from annually mined natural NU (another variable) plus that generated by the already-built breeders. When the total time INPUTed (NUM which for 2100AD =’s 81) is reached, the program stops looping and prints out how many reactors exist and how much uranium had to be mined/processed to get them all started.

Let’s assume that we want to build 30 TWe’s worth of sustainable nuclear power plants by 2100 AD. If we start building them beginning with 1900 tonnes of spent fuel RGPU + excess weapons grade fissile and each start up requires 5 tonnes of fissile, we’ll have about 807 total GW\textsubscript{e} of nuclear power (400 LWRs and 407 breeders) at the end of twenty years. From then on, the amount of freshly mined NU required to start 30,000 reactors by 2100 AD depends upon their CR – if they are isobreeding (CR=1.00), nearly 23,000,000 tonnes of fresh NU must be mined/processed. If they make 20% more fissile than they consume (e.g., CR =1.2, the figure attributed to the Russian BN-350), only 7,000,000 tonnes of NU would be required. The former figure is about 25% greater than the uranium industry’s 2014 Redbook’s best guess of total “proven plus undiscovered resources”.

Such calculations reveal that it is indeed possible to become 100% sustainably nuclear powered with such reactors by 2100 AD but only if

\textsuperscript{110} APPENDICES I & II go through some examples of how spent LWR fuel could be converted to fuels compatible with breeding-capable MSRs.
we start soon and quit “burning our seed corn“ (\(^{235}\text{U}\) and \(^{239}\text{Pu}\)) in today’s or any other sort of inefficient nuclear reactors\(^{111}\).

Again, the exception to this would be LeBlanc’s tube-in-shell reactor concept because it should require far less startup fissile – likely under 2 tonnes \(^{235}\text{U}\) - to get a GWe’s worth of isobreeding reactors up and running (depends upon reactor size/shape). If that turns out to be the case, then building my scenario’s 30,000 full sized breeders would take far less time and NU; i.e., it could probably be completed by 2060AD utilizing the same amount of “new NU” as would continuing to run today’s ~400 equally powerful LWR’s (see APPENDIX VI).

In this respect, it’s a good thing that the USA’s approach to radioactive waste management is dysfunctional – much of the fissile inventory required to initiate a sustainable nuclear renaissance is now considered “waste” – the management of which received a great deal of “study” resulting in actions/programs that didn’t work out as planned/hoped/promised. For example, SRL’s MOX boondoggling means that its 34 tonnes of “excess” almost pure \(^{239}\text{Pu}\) still exists in a useable condition and almost everyone who worked on that project is richer than he/she would have been if no such work had been available (Uber & Lyft can employ only a limited number of the USA’s downsized nuclear engineers and scientists).

\(^{111}\) For example, during INL/Argonne’s IFR project’s last few years, its designers/modelers were told to deliberately reconfigure it to maximize “waste” burn up; i.e., waste as much precious startup fissile as possible. That’s why Argonne’s workers decided to switch the name of what they were working on from IFR to SFR (“sodium fast reactor”). Personally, I find it difficult to be cynical enough about what routinely happens within DOE’s nuclear complex.
Another example of how DOE’s now-traditional approach to nuclear project management might turn out to be a good thing is that the Navy’s spent naval reactor HEU remains in a form (undiluted with $^{238}$U) capable of serving as a genuinely sustainable molten salt reactor’s start up fissile.

Simultaneously reestablishing the USA’s “leadership in nuclear power”, cleaning up its atmosphere, restoring/maintaining the fertility of its farmland, and creating millions of worthwhile jobs (not just temporary service-type gigs) and high-tech business opportunities for its citizens would be worth doing whether the reactors enabling it would cost $860 billion or three times that much. For comparison, Mark Jacobson, Stanford University’s Pied Piper of the “green new deal” movement, estimates that his 100% wind, water, and solar powered alternative (WWS) would cost us about $13.4 trillion paid for with big cuts in military spending, a very high carbon tax, and more highly taxed “wealthiest Americans” – not the bond drives which would give the average US citizen a bigger personal stake in the outcome of any such campaign.

Of course, since I’m pretending here that the world’s total human population will become 11.2 billion, the cost of the ~30 thousand full-sized reactors required to comfortably power everyone in it would be proportionately higher, ~30 (or 60) trillion of today’s dollars. To put that number into perspective, it’s ~12% of what the “power walls” capable of backing up a similarly capable solar panel and/or windmill-based energy supply system for just one day would cost them.

“Special” materials that wouldn’t be required by any of these nuclear reactors include the China-sourced rare earths required to make the relatively light-weight generators within the nacelles of most of today’s
wind turbines. There’s no such weight requirement for any sort of ground-sited electrical generator, so nuclear power plants don’t need them.

Green campaigners love wind turbines, but making their permanent magnets is environmentally impactful – to China, that is (Hurst 2010). China currently meets about 96% of the world's demand for rare earths, and most of the so-required mining, separation and extraction is done there. Every ton of rare earth element (REE) produced, apparently generates 9,600 to 12,000 cubic meters of dusty waste gases containing, hydrofluoric acid, sulfur dioxide, and sulfuric acid, ~ 75 cubic meters of acidic wastewater, and about one ton of relatively concentrated radioactive waste residue. China’s Baotou region produces approximately ten million tons of such wastewater every year most of which is discharged without effective treatment and thereby contaminates both potable water and that used for irrigation. Disposal of the approximately 2000 tonnes of mildly radioactive mine tailings112 generated per tonne REE is also problematic. Generally, tailings are placed into large open impoundments whereas in the U.S. permits are required and such waste piles must be properly covered or remediated in some other fashion.

A 2MW wind generator’s permanent magnets require about 930 pounds (0.426 tonnes) of REE which means that building a wind farm with an  

112 Again, the reason why such stuff is somewhat radioactive is that REE and thorium are chemically similar and therefore usually present in the same ores.
average CF of 0.3 capable of providing as much energy per year as a 1 GWe MSR would require about 724 tonnes of rare earths - mostly neodymium (Stover 2011).

To quantify this in terms of environmental impact, let’s assume Hurst’s contention that the mining/processing of one ton of rare earth minerals produces about one ton of fairly concentrated radwaste. In 2012, the U.S. added about 13.1 GW of wind power capacity which figure means that about 2770 tonnes of rare earths were used in the wind turbines installed here that year. It also suggests that about 2770 tonnes of the above-mentioned radioactive waste were created to make them.

To put that number into perspective, America’s nuclear power industry produces about 2000 tonnes of spent LWR fuel “waste” each year. This means that the U.S. wind energy industry may very well have created more tonnes of radioactive waste that year (in somebody else’s back yard, of course) than did its nuclear power industry. In that sense too, the USA’s nuclear industry is relatively clean because it generated about 20% of its electrical energy that year while wind accounted for just 3.5 percent.

### 6.3 Waste management costs

“...eventually the antinuclear groups found the soft underbelly of the industry. It was something that had remained in the engineering background for decades. It was not nearly as exciting as striving for plutonium breeder reactor configurations or ceramic cores for jet engines, but it was there, and it was a distant bother. It was a nag, it was the long term disposal of all the radioactive byproducts of nuclear fission.” (Mahaffey 2009 p 304)
Since the US is one of the world’s most litigious countries, its reflexive anti nukes quickly realized that rendering waste management unnecessarily difficult would serve their purpose. That plus the fact that DOE could be depended upon to spend lots of money “studying” it and then not accomplish much, turned reprocessing waste management into one of the biggest hurdles that a nuclear renaissance must get over.

The “should costs” of my scenario’s waste management would be small because relatively little waste would be generated and it would be simple to first treat and then dispose of. Unlike today’s fuel cycle, its waste would “burn” almost all of the especially troublesome long-lived transuranic radionuclides and thereby consist of only relatively short-lived fission products. The mass of such waste generated by 22 TW_e’s worth of MSR-type power each year would be about 18,000 tonnes. Depending upon the type of reactor used, when everything required to isolate those fission products is combined with them and converted to glass, that glass would weigh from 15 to 40 tonnes/GW_e/year and occupy 5-13 m^3 of space/year (Siemer* 2013 & Siemer* 2014). These figures correspond to a total annual disposal volume ranging from 0.00015 to 0.00038 of one percent of that of the ash currently being generated by the world’s coal-fired power plants and dumped somewhere each year.  

113 Like mining wastes, coal ash often ends up behind huge earthen dams increasingly vulnerable to global warming-enhanced flooding. The resulting almost inevitable disasters routinely kill many people and pollute huge swaths of land downstream of those impoundments.  
toxic trace metals (e.g., cadmium) all of which possess infinite half-lives. This means that coal represents a much greater (and proven) threat to both the environment and the people in it than does the waste generated by today’s or the future’s nuclear power plants.

6.3.1 Waste Treatment
Vitrification has been recognized to be the “Best Demonstrated Available Technology” (BDAT) for radwaste immobilization for about four decades. One of the reasons for this is that vitrification is intrinsically both simple and cheap which is why real world glasses typically cost under $3000 tonne - too cheap to be worth recycling in many places. Because the temperatures required to make them, are dangerously high (typ. 1000-1300°C), all glass making is done more or less “remotely” within thick-walled and thereby heavily “shielded” radiation-wise melters. Consequently, there’s not much reason to assume that the cost of “remotely” making a radioactive glass should be vastly more than that, let’s say $10,000 per tonne. Given that figure and a 15% mass-wise waste loading what would it cost to vitrify the ~18,000 tonnes of radionuclides generated/a producing 22.4 terawatts worth of breeder reactor power?

Tonnes of glass per year = 18000/0.15 =120,000 tonnes

Glass cost/a = $10,000/t*120,000 t/a=$1.2 billion/a

Vitrification cost per kWh = $1.2 billion/(22.4E+12 J/s*3600 s/hr*24 hr/day*365 days/a/3.6E+6 J/kWh) = $6.1E-6/kWh (trivial!!)

6.3.2 Waste disposal
Disposal of such glass shouldn’t be prohibitively expensive either because one of the USGS’s senior-most geologists (Winograd 1981), described a cheap way to accomplish it almost 40 years ago. Here’s that paper’s abstract:
“Portions of the Great Basin are undergoing crustal extension and have unsaturated zones as much as 600 meters thick. These areas contain multiple natural barriers capable of isolating solidified toxic wastes from the biosphere for tens of thousands to perhaps hundreds of thousands of years. An example of the potential utilization of such arid zone environments for toxic waste isolation is the burial of transuranic radioactive wastes at relatively shallow depths (15 to 100 meters) in Sedan Crater, Yucca Flat, Nevada. The volume of this man-made crater is several times (i.e., ~ 5 million m$^3$) that of the projected volume of such wastes to the year 2000. Disposal in Sedan Crater could be accomplished at a savings on the order of 0.5 billion, in comparison with current schemes for burial of such wastes in mined repositories at depths of 600 to 900 meters, and with an apparently equal likelihood of waste isolation from the biosphere.”

That single, already radiologically contaminated/excavated, huge pit situated in the USA’s most worthless desert could contain 20–50 years-worth of the future’s HLW “waste forms”.

The scientific basis of Dr. Winograd’s concept was subsequently thoroughly investigated by SANDIA scientists, who dubbed it “Greater Confinement Disposal”. It was subsequently implemented in the Nevada (bomb) Test Site’s (NTS’s) nearby “area 5” (APPENDIX X goes further into that story). A properly-sited GCD-type repository is key to solving the USA’s interminable defense type radwaste boondoggling because it would eliminate the single greatest action-paralyzer/cost-driver in its approach to radwaste management – the ridiculously high volumetric costs assumed for such waste's burial plots which, in turn, serves to rationalize its decision makers’ insistence upon trying to isolate such waste’s highest stuff from everything else. Such huge scale, fully
“remoted”\textsuperscript{114} attempts at entropy-reversal are both unnecessary and prohibitively expensive.

Dr. Winograd’s estimate (0.5 $\text{billion}$) seriously underestimated the cost of DOE’s ensuing radwaste burial schemes. It is also likely that he didn’t suspect that DOE would end up charging US taxpayers roughly $1 million for each tonne (about 0.4 m$^3$) of “high level” glass that its contractors manage to produce\textsuperscript{115}. The sole exception that I’m aware of was its one and only “Vitrification and Privatization Success” (Picket et al 1995). In that instance, a contractor (Duratek) promised to and then actually did convert 670,000 gallons of the Savannah River Site’s liquid “mixed” (both radioactive and chemically toxic) radwaste plus some” hot” dirt and sludges to \textasciitilde{}1700 tonnes of glass “gems” for $13.9$ million (\textasciitilde{}$8400$/tonne). Tougher-to-produce (higher melting) real-world bottle/window glass currently costs under $3000/tonne which renders it too cheap to be worth collecting/recycling in much of the USA.

“32N164W”, Chapter 16 of Gwyneth Craven’s “Power to Save the World” describes another competent, low cost waste disposal scenario thoroughly investigated by scientists competent to do so. GOOGLE

\textsuperscript{114} Almost all activities involving “hot” radioactive materials are performed “remotely”, i.e, from a safe distance with shielding imposed between them and human operators.

\textsuperscript{115} Again, in the DOE Complex, most of “vitrification’s” cost is due to the separation activities (aka, “pretreatment”) preceding it in order to minimize the volume of the “high” fractions destined for its especially volumetrically challenged imaginary repositories. By August 2013, the Savannah River Site’s glass melter had produced 3728 stainless steel canisters containing about 1.72 tonnes of glass each. That facility started up in 1996 and has received about $0.55$ billion 2013 dollars per year since then. That works out to a glass cost of $1.46$ million/tonne. Real world bulk glasses cost under $2000$/tonne. 

http://srremediation.com/dwpf_40_canisters.html
EARTH reveals that it refers to a spot situated near the center of the Pacific Ocean far from the edges of any continental plate where the water is about twenty thousand feet deep and the basaltic bedrock underlying it covered with a ~thousand foot deep layer of soft pelagic mud/ooze. It’s simultaneously about the most stable, most isolated, and least valuable piece of the earth’s surface. Her chapter does a fine job of explaining why the World’s top geoscientists concluded that it represents a truly excellent radwaste disposal site: big torpedo-shaped, steel encased glass (or concrete) radioactive waste forms dumped off a ship there would bury/spear themselves deeply within that mud thereby isolating their contents from the biosphere for millions (billions?) of years.

If such ships were to be powered with little THORCON or Terrestrial Energy IMSRs instead of diesel engines, transporting such radwaste forms to that disposal site wouldn’t even be polluting the environment. The diesel fuel currently consumed by ships is a sulfurous, tar-like, “bunker oil” - not the relatively clean stuff sold by the first-world’s service stations. It’s literally the “bottom” of the barrel” both quality and impurity-wise which is why it’s “suitable” only for an application that pollutes a “commons” (the oceans) rather than anyone’s private property.

Incidentally, the world is already experiencing a steadily worsening “spent solar panel waste crisis”. (To learn about this, see Tomioka 2016).

It is unlikely that Goeller & Weinberg’s cornucopian world could be implemented by either the world’s poorest people themselves or the institutions that have traditionally provided most of their aid. Avoiding a deadly “hothouse earth” will require the simultaneous redirection of humanity’s actions from selfish, for-profit exploitation to genuine
stewardship and rapid transition to a genuinely sustainable economic system (Steffen 2018). It won’t be cheap or easy because rendering the world’s energy systems GHG free, ensuring that its land, water and other resources are used sustainably, adapting to climate change and cleaning up an already polluted world will require changes that many influential people and the vested interests that they own/control will resist. The western world’s national policies are largely shaped by the neoconservative belief that a market economy is the life force of civilization and that consumption is its purpose, thereby creating its jobs, wealth and material prosperity (Ayn Rand has become some of their leaderships’ most-admired intellectual). That paradigm holds that producers will act for the common good guided by “sovereign” consumers without interference from government. By their thinking, if we just exhort individual consumers to purchase “green” products and services, we will eventually arrive at a clean/green/prosperous/fair form of capitalism. While there is some truth to that notion, it’s inconsistent with the realities of corporate power and humanity’s self-interest in general. Corporations seek to maximize gains for their managers and shareholders and minimize environmental and other nonmarket obligations. That’s why there are far more lawyers and lobbyists in Washington DC than elected “public servants”. In a technological civilization containing millions of enthusiastic, intelligent, and eminently trainable young people, “saving the world” is really a political, not technical, problem and success will require the same extremely rare combination of technical smarts, unflinching

116 In practice, those drivers translate to an economic system based upon “let the buyer beware” which also makes it difficult for buyers to determine what they’re getting for their money (the technical details of the things we buy is often considered “proprietary” information)
commitment and hard-headed management skills exhibited by both General Groves and Admiral Rickover more than a half-century ago – not management exhibiting the symptoms of the majority of the USA’s recent nuclear initiatives (Abdulla 2017, Ford 2017).

Of course the problem is that DOE hasn’t bothered to do the research necessary for anyone to decide what a Rickover-like program manager should build for us.

The following are the DOE nuclear project management “symptoms” identified by the National Academy’s all time “best seller”, “Barriers-to-science-technical-management-of-the-department-of-energy Environmental Remediation Program” (NAP 1996) over two decades ago.

1. Planning that is driven by existing organizational structures rather than problems to be solved.
2. Commitments that are made without adequately considering technical feasibility, cost, and schedule.
3. An inability to look at more than one alternative at a time.
4. Priorities that are driven by narrow interpretations of regulations rather than the regulations’ purpose of protecting public health and the environment.
5. The production of documents as an end in itself, rather than as a means to achieve a goal.
6. A lack of organizational coordination.
7. A “not-invented-here” syndrome at individual sites.

An earlier report by the Galvin Commission (Galvin 1995), revealed a “counterproductive federal system of operation” for DOE’s national labs, saying, “the current system of governance of these laboratories is broken and should be replaced with a bold alternative”. The problems it identified included, “increased overhead cost, poor morale, and gross inefficiencies as a result of overly prescriptive Congressional management and excessive oversight by the Department,” and “inordinate internal focus at every level of these laboratories on
compliance issues and questions of management processes, which takes a major toll on research performance.”

Those outsider-generated reports had about as much effect upon DOE’s subsequent behavior as does a spritz from a child’s squirt gun upon a flock of ducks. Similar efforts by insiders (APPENDICES VII & VIII) didn’t cause its decision makers to “embrace change” either.

6.4 How do we pay for all this change?

The most “obvious” source of the money required for the USA to develop and then implement a clean, green, nuclear powered future is its tremendously bloated defense budget. The majority of such spending is nominally “discretionary” meaning that it could and should be used to address the energy-related technical issues affecting national security noted by a number of very senior military officers (CNA 2014).

Other obvious funding sources include:

- Revise the USA’s tax structure to be more like it was back when America was genuinely “great” (late 1930’s to circa 1970); i.e., heavily tax inherited wealth and raise the uppermost marginal income tax rate to at least 90%. Doing so would level the playing field for succeeding generations of US citizens and raise some (not most) of the money required for nation rebuilding. During 1944–45, “the most progressive tax years in U.S. history,” the rate applied to any income above $200,000 ($2.4 million in 2009 dollars) was 94%. WWII’s tax law revisions increased the number of “those paying some income taxes” from 7% of the U.S. population (1940) to 64% by 1944.
Issue “Nuclear Green New Deal bonds”: The last time the United States issued what were then called war bonds was during WWII when full employment collided with rationing and they represented a good way to remove money from circulation and reduce inflation. Issued by the U.S. Government, they were first called defense bonds, which name was switched to War Bonds after the Japanese attacked Pearl Harbor. Bond rallies were held throughout the country with celebrities to enhance advertising effectiveness. Free movie days were held in theaters nationwide with bond purchases serving admission and all proceeds deposited into the U.S. Treasury. In those days a median US yearly income was only about $2,000 despite which 85 million Americans — over half its population — purchased bonds paying about two thirds of that war’s total cost.

Carbon taxes most of which should be rebated directly to individual citizens, not spent by politicians.

The USA’s Manhattan project cost about $2 billion 1940 dollars (~$36 billion 2019 dollars). In just over three years, its workers turned a rather abstruse scientific observation\(^\text{117}\) into massive technical infrastructure that succeeded in abruptly ending WWII and thereby likely saving a half million US lives. The USA’s WWII bond drives raised over ninety times that much money, $185.7 billion 1940 dollars ($3.2 trillion 2019 dollars).

\(^{117}\) Over Christmas vacation in 1938, physicist Lise Meitner and chemist Otto Frisch made a discovery that revolutionized nuclear physics and quickly lead to the atomic bomb; i.e., that when \(^{235}\text{U}\) absorbs a neutron, it usually (about 80\% of the time) splits into two smaller atoms (fission products) and 2 or 3 “new” neutrons.
A recent evaluation of thirty-three studies looking at the return on investment (ROI) of infrastructure investments suggests that smart infrastructure development programs like the ones that China’s been doing exhibit a 10-20% rate of return in terms of increased economic activity (Bivens 2017). That suggests that the federal government’s borrowing money from its citizens to first develop and then implement a “nuclear green new deal” would be a really great investment. I suspect that I’m not the only US citizen who would be delighted to have an opportunity to invest in something like that rather than in the mysterious “financial products” that my financial advisor has my savings invested in now.

Chapter 7. The nuclear establishment’s self-inflicted wounds

Goeller and Weinberg’s utopian future can’t come to pass if those individuals most able to bear the cost of the necessary sweeping changes — those who’ve benefited the most from today’s economic and political systems — don’t help to pay for it. Since interfering with current business practices and taxing excessive wealth are anathema to most of the Western world’s political leaders, it’s likely that Eastern not Western counties will become the “outsiders” helping the world’s disadvantaged people to implement this or any other scheme capable of achieving its goals. One reason for this is that most of the West’s decision makers seem to believe that nuclear power’s technical innovation should be left to the private sector, not government. While that might make sense for IT (hardware, software, and cell phone app development), it is unlikely to work for this purpose because reactor development is much “riskier” requiring a far greater investment of money, time, special materials, experimental work, and technical experts
able to address a host of tough mechanical, physical, chemical, and, especially, legal issues – it can’t be done by a few clever “hackers” in a rented garage. Its goals – achieving genuine sustainability, preventing further environmental damage, and providing a better life for everyone including the poor several decades off in the future – are also inconsistent with those of the majority of today’s politicians and venture capitalists. Getting government “out of the way” might sound nice but won’t work because every major energy breakthrough in recent history has received public support that moved an idea to proof-of-concept to demonstration after which the private sector heavily invested and thereby became richer (Siddiqui 2018).

Of course, the other reason is that many of the Western world’s decision makers have apparently been sold on the notion that the future should/could be adequately powered by an “all of the above” mix of politically correct (non-nuclear), renewable technologies (see Jacobson 2009, Jacobson 2017, and, for opposing views, Bryce 2013, Beckers 2016, Clack 2017, Maloney 2018, and Brook 2018), and, have therefore supported/subsidized efforts consistent with that paradigm. Also, even if those decision makers weren’t overtly hostile to anything “nuclear”, they paid only lip service to the development of a sustainable nuclear fuel cycle. This is understandable because nuclear power’s champions haven’t presented a particularly compelling case\textsuperscript{118} and the majority of US politicians were originally lawyers and/or businessmen, not engineers or scientists, and therefore don’t think quantitatively about

\textsuperscript{118} For the most part, its spokespersons haven’t been championing anything that could “save the world” because doing so would require them to challenge the industry’s leadership’s assumptions and business models
technical issues – especially anything that’s “controversial” and/or not apt to be too obvious to ignore until their political career is over. Of course the people that work for them in the USA’s more-or-less privatized national laboratory system\(^{119}\) (e.g., INL, ORNL, Hanford…) pretty much have to do whatever those politicians want because becoming a “poor team player” in that sort of working environment amounts to career suicide.

The most accurate measure of any country’s commitment to accomplishing anything is how much money it is willing to spend trying. In the world’s richest Western nation (USA ~ $20 trillion GDP) we hear things like, “The US Department of Energy (DOE) has selected projects to develop a pebble bed reactor and a molten chloride fast reactor to receive multi-year cost-share funding worth up to a total of $80 million.” (DOE 2018), and, that “Secretary of Energy Rick Perry Announces $60 Million for U.S. Industry Awards in Support of Advanced Nuclear Technology Development”, which support is to be split between 13 projects in 10 different states (Perry 2018). Although much of this work will be performed in the government’s laboratories by its contractors’ employees (it’s illegal to do genuinely “hot” research elsewhere in the US), its leadership won’t assume responsibility for

\(^{119}\) Since the Manhattan Project, the management of DOE’s sites has been done by private M&O contractors. DOE spends 90 percent of its budget on those contracts making it the government’s largest non-Department of Defense contracting agency. Although each site nominally operates under DOE’s oversite, they work more or less independently of each other because their M&O contactors are, in effect, competing with each other for DOE’s next contracts. This plus the revolving-door shuffling of top-level managers back and forth between government, industry, and “independent” advisory groups generates a tremendous amount of duplication/overhead constitute a root cause of the USA’s notoriously inefficient nuclear project management.
guiding it or insist upon appropriate goals. Finally, although these projects have accomplished a good deal of computerized modeling, simulation, and “road mapping” (see Appendix IX and DOE’s http://gain.inl.gov website), DOE’s nuclear scientists/engineers can’t effectively address the future’s energy issues until they become empowered to do the same sorts of “risky” experimentation performed at its National Reactor Testing Station (NRTS), now INL, during the 1950’s & 60’s. Unfortunately, although those efforts successfully designed, built, operated, and then safely decommissioned ~50 different reactors, the USA never built a test reactor capable of evaluating today’s front-running MSR concepts and apparently is still not planning to do so (see Petti 2017).

In contrast to its “pretend” commitment to nuclear energy research and development, the USA’s DOE/NNSA spends ~$6.9 billion/a to maintain its stockpile of nuclear weapons and its total (DOD+DOE) nuclear weapons-related expenditures are on the order of $20–40 billion/a (Rumbaugh and Cohn 2012). “Nuclear modernization” is a euphemism covering a wide range of secretive activities that constitute in the view of many, a new, dangerous, and again, fabulously expensive global nuclear arms race. In the United States, the 30-year cost of the plethora of programs under its “nuclear modernization” umbrella – including new nuclear-capable bombers, land-based nuclear missiles, “mini bombs”, and nuclear submarines – has recently been estimated at $1.2 to $1.7 trillion. Observers familiar with the Defense Department’s $640 toilet seats suspect that if that entire modernization program were to be funded and carried out, its cost would be much higher even than that (Mecklin, 2019).
Here’s a more up to date (10Jul2018) example of DOE’s commitment to developing a sustainable nuclear cycle.

“U.S. Department of Energy Provides Nearly $20 Million for Domestic Advanced Nuclear Technology Projects”
https://www.energy.gov/ne/articles/us-department-energy-provides-nearly-20-million-domestic-advanced-nuclear-technology

Here’s a breakdown of those awards.

$ million  Funded activity
7.00  Calendar Year 2018 Activities for Phase 2 of NuScale Small Modular Reactor project (a mini PWR)
0.498  Regulatory Support for Advanced Light Water Reactor Deployment: Advanced Boiling Water Reactor Source Term Reduction
6.314  Advancing and Commercializing Hybrid Laser Arc Welding (HLAW) for Nuclear Vessel Fabrication
2.101  Fluorination of Lithium Fluoride-Beryllium Fluoride (FLiBe) Molten Salt Processing – Flibe Energy
1.120  Experimental Verification of Post-Accident Integrated Pressurized Water Reactor (iPWR) Aerosol Behavior, Phase 3
1.925  Reactor Plant Cost Reduction to Compete with Natural Gas Fired Electrical Generation (Hitachi small modular BWR)
0.400  Conceptual Engineering for a Small Modular Reactor Power Plant Based on Lead-Bismuth Fast Reactor (LBFR) Technology

Finally, “DOE has selected two companies to receive GAIN technology development vouchers in this second review cycle. The companies selected are Yellowstone Energy (Knoxville, TN) in the amount of
$160,000, and ThorCon US (Stevenson, WA) in the amount of $400,000. Further detail and description of these awards can be found under the GAIN website.” (Same reference)

Note that of DOE’s $19.9 million commitment to “advanced” reactor development, only $2.5 million went to help develop anything having to do with a sustainable nuclear fuel cycle (Flibe Energy’s fluorination demonstration and the Lead-Bismuth Fast Reactor’s (LBFR) conceptual engineering).

“The President's Budget provides a total of $32.5 billion, $30.2 billion in discretionary funding and $2.3 billion in new mandatory funding in FY 2017 to support the Department of Energy in the areas of nuclear security, clean energy, environmental cleanup, climate change response, science and innovation”. https://www.energy.gov/fy-2017-department-energy-budget-request-fact-sheet

$2.5 million represents 0.0077% of DOE’s budget and will be mostly spent supporting people working on “safe” (not risky) projects within its national laboratories.

James Mahaffey recently characterized the nuclear establishment’s cultural norms as follows:

“Under fire nuclear engineering is to engineering as modern Islam is to religion. It’s become more conservative and fundamentalist. Criticism from outside was so severe that internal criticism became more than the system could tolerate. The designs of nuclear reactors, plants, auxiliary
mechanisms, and associated facilities, such as “waste” disposal systems or fuel handing strategies, all become more conservative\textsuperscript{120}, with less engineering risk or innovation.” (Mahaffey 2009, p. XVI).

That culture manifests itself within DOE’s nuclear complex as an over reliance upon authority, “procedures” (see APPENDICES VII, VIII, and XII), fine-sounding but irrelevant principles, secrecy, and a tendency to shade the truth a bit when dealing with outsiders (\textit{if hard pressed, tell the truth but never the whole truth if there’s any way it can be avoided} - see APPENDIX XII).

Government’s role in this arena should be to fund long term, revolutionary projects, not sustaining and incrementally improving an already well performing LWR technology - that should be the domain of private industry. Government’s job is to retire a \textit{worthwhile} concept’s risks so that private enterprise can then step in and capitalize upon that effort. Unfortunately, instead of restricting its scope to areas where academia and industry lack the funding, people, or facilities needed to innovate, DOE’s nuclear engineering office (hereafter designated “NE”) is engaged across the USA’s entire nuclear enterprise, spreading its focus and expenditures over myriad, disparate, & mostly not cutting-

\textsuperscript{120} An American-type conservative embraces political beliefs characterized by respect for “business”, American traditions, republicanism, support for Judeo-Christian values, “business”, anti-communism, individualism, “business”, advocacy of American exceptionalism, and defense of Western culture from threats posed by foreigners, socialism, authoritarianism, and moral relativism.

Franklin D. Roosevelt said it even better: “A conservative is a man with two perfectly good legs who, however, has never learned to walk forward.” .

edge, activities. Evidence of its lack of focus is the blizzard of road
mapping and strategy documents prepared by its employees. The thirty
anonymous experts interviewed by Ford et al. (Ford 2017) characterized
NE’s activities as follows:

1. “Yes, we have enough roadmaps to publish an atlas. And yet, no
   vision.”

2. NE's real goal is to maintain its funding stream, “flying under the
   radar to the greatest extent it can in order to avoid political controversy,
   and it generally succeeds at that.”

3. NE’s project funding is an “old boys’ club,” where investigators
   are funded, “if NE had funded them in the past.”

4. NE favors funding “known quantities” in order to “prevent
   surprises.” Evidence of good performance or innovative research rarely
   comes into the equation121.

5. NE is most definitely not interested in “taking risks:” it neither
   rewards nor encourages radical deviations from its programming norm.

Those experts lamented the fact that the USA’s nuclear R&D enterprise
is led by an organization that avoids taking risks and making hard
decisions, frowns upon ambitious, long-term projects, funds them at a
low level and is primarily concerned with the next appropriations cycle.

More than two-thirds of them opined that NE’s national laboratories
ought to be mainly a facilitator, or enabler, of research. They should

121 Again, within NE, a project’s products are reports (“paper”) and, occasionally, a decision –
nothing concrete.
conduct high-risk and potentially high-reward research and maintain the facilities that buttress industrial innovation, as opposed to micro-managing its activities.

7.1. Refusal to choose/set rational goals

There’s been a great deal of confusion about what a nuclear renaissance should do and even more about what its implementation issues would be. In spite of the fact that almost everyone working for DOE knows that we live in a world that will soon need far more “new” clean energy than Jacobsen et al.’s 100% wind, water, and solar power scheme could supply to a world containing >11 billion people, its decision makers refuse to admit that that’s the primary reason for nuclear engineering/scientific research and development. Consequently they encourage (force) the people that work for them to devote their efforts to developing reactors/fuel cycles suited for addressing short term political issues; i.e., “less proliferative”, “smaller”, “modular”, “idiot proof”, “zero risk”, “waste burning”, “simpler”, etc.¹²², not saving the world. It’s unreasonable to expect individuals working within any such top-down driven system to devote much attention to developing anything capable of providing 100% of our grandchildren’s energy.

Let’s take a look at some examples.

7.1.1. NGNP

¹²² For instance, during most the last two decades, it’s been verboten to use the word “breeder” in any report describing reactor concepts that DOE was considering. That’s like telling NASA’s engineers that they can no longer mention (or consider) “rockets”.
A recent such example was DOE NE’s “Next Generation Nuclear Power” (NGNP) boondoggle intermittently funded from 2005 to 2013. Its champions invoked huge, high pressure, helium cooled, graphite moderated, solid-fueled, “very high temperature reactors” in order to generate hydrogen somewhat more efficiently (i.e., chemically) than does water electrolysis\textsuperscript{123}. Of course, doing that would require that its new high temperature gas cooled reactor (HTGR) operate at very much higher temperatures (\(\sim 1000^\circ C\)) than had any of the other gas-cooled reactors previously built/tested, meaning that lots of time and money would have to be spent developing “special materials”. HTGR represents an old, much investigated, and commercially unsuccessful reactor concept\textsuperscript{124}. It turned out that such material would be extremely

\textsuperscript{123} During this period, circa 2000-2013, DOE’s vision for the future invoked a “hydrogen economy” in which most of the things currently powered with petroleum would be powered with hydrogen instead. That never made much sense because hydrogen is an extremely volumetrically challenged energy carrier (not fuel) – at normal atmospheric pressure, burning it generates \(0.00034\) as much heat as does burning same volume of petroleum. While fuel cells are 2-3 times more energy efficient than are hydrogen-burning heat engines, it’s still very difficult to imagine how cars and trucks could be safely powered with it due to its uniquely low mass and boiling point - tanks strong enough to carry the equivalent of 10 gallons of gasoline would be impractically big/heavy. Second, if we really wished to make more hydrogen, the goal should be to generate electricity more sustainably and cheaply, not to come up with yet another “advanced” converter-type (unsustainable) reactor concept that could only be built of unobtanium.

\textsuperscript{124} The last “serious” attempt to get a HTGR up and running ran from 1993 to 2010 in South Africa. It would have been the first Generation IV unit to enter the construction phase (but didn’t). Its pebble bed (PBMR) design was based on a German technology demonstrated during the 1970s and 80s. It was to be graphite moderated and helium cooled with a closed-cycle gas turbine based on the Brayton thermodynamic cycle. It had a proposed thermal output of 400MWe and electrical output (net) of 160 MWe. Its fuel would comprise thousands of \(\sim 6\) cm diameter spherical graphite “pebbles”, each filled with thousands of tiny silicon carbide and pyrolytic carbon coated \(\text{UO}_2\) particle, tristructural isotropic (TRISO) fuel kernels which were supposed to retain all fission products. Its fuel pebbles had a life expectancy of three years and were to be
expensive (or outright impossible) to make and, since any such fuel would be almost impossible to “reprocess”, it would also be almost impossible to render any such system genuinely sustainable. Consequently, DOE’s best and brightest nuclear scientists and engineers wasted another decade studying something that the USA’s civilian nuclear industry wasn’t interested in and doesn’t represent a practical solution to the world’s long term energy problems.

The NGNP program’s other issues were largely due to NE’s lack of programmatic discipline. It tends to micromanage its grants to an intrusive extent; it rarely follows through on any advanced, non-light water reactor project; it does not fund them at the level or duration necessary for project success; and, it is so attuned to political sensitivities that it often abandons just-started programs in favor of others deemed more politically palatable. Some factors beyond NE’s control such as the inflexible cost-sharing arrangements mandated by Congress and the Office of Management and Budget (OMB) also make it difficult for industry to collaborate with it.

Of the approximately 400 papers and posters presented at the IAEA’s latest international conference having to do with “Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development (FR17)” (IAEA 2018), four presentations were made by people representing the USA – one was about DOE’s latest road mapping efforts, two about its long-defunct LMFBR program, and one circulated through the core about six times before replacement. DOE’s NGNP project designers assumed that their new & improved TRISO kernels would be embedded in big prismatic graphite logs fixed within the core, not circulated, until their fissile had burned up.
by an antinuke anxious to remind everyone that anything nuclear could be dangerous.

Another reason for the USA’s poor showing at such international gatherings is that its current regulations criminalize many of the activities intrinsic to international cooperation\textsuperscript{125}. Bill Gates recently summed up that situation as follows, “\textit{Unfortunately, America is no longer the global leader on nuclear energy that it was 50 years ago. To regain this position, it will need to commit new funding, update regulations, and show investors that it’s serious}” (Gates 2018).

Those cultural characteristics along with a number of embarrassing multi-billion dollar boondoggles have led many outsiders to be leery of anything having to do with nuclear power.

In a finite world, money wasted doing unnecessary things is money that can’t be spent doing necessary things. Let’s take a closer look at some of those unnecessary expenditures.

\subsection{7.1.2 DOE’s Savannah River Site’s MOX boondoggling}

\textsuperscript{125} For instance, any research finding that the DOE’s bureaucrats deem potentially useful to “enemies” is classified and thereby unavailable to anyone else working on the same problem. One of the most absurd manifestations of that mindset was that during the early 1980’s, someone blanked-out the symbol for -----(-) on our lab wall-mounted periodic table because it was the “secret” element rendering the USA’s nuclear navy’s metallic zirconium/uranium fuel assemblies extra special. I guess the rationale was that any Russian spy who broke into our lab wouldn’t be able to figure out what that mark was covering. The modern periodic table was invented by a Russian, Dmitri Mendeleev, 150 years ago and the USA doesn’t possess secrets about reactors that the Russians and Chinese don’t already know (if anything it’s probably now the other way around).
After considerable study during in the early 2000’s, DOE concluded that the best/cheapest way to “manage” the US federal government’s ~34 tonnes of surplus weapons/bomb-grade plutonium would be to fabricate MOX (mixed oxides of plutonium and uranium)-type fuel for US civilian power plants. This isn’t a novel idea or even a particularly difficult thing to do because the French, British, Russians, and Japanese had already been making MOX of the far more radioactive, poorer quality (lesser fraction of $^{239}$Pu) “reactor grade plutonium” recovered by their fuel reprocessing operations. Such fuel’s proposed US customers didn’t really want it because it’s relatively “hot” and would therefore likely cost them more in terms of increased training and regulatory overhead than it would be worth. Construction started in 2007 but DOE’s management program “symptoms” (NAP 1996) combined with the political pull of So Carolina’s politicians quickly turned that project into another profitable (for them) boondoggle. In 2007, DOE’s experts promised that its MOX plant would cost $4.8 billion and be completed.

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126 In DOE-speak, “waste management” might mean anything from the “no action alternative” (doing nothing which in cases like INL’s already calcined wastes or SRS’s “excess” bomb grade Pu, is likely the best option) to promising to transmute whatever it is to diamonds and ship them to the other side of the moon. It shouldn’t surprise anyone that such exercises’ almost inevitable “mission creep” tends to be in reverse. In the DOE contracting business, the biggest liar usually wins, which means that DOE does lots of goal post shifting to cover its mistakes.

127 Which decision apparently ignored Bolgren et al.’s conclusion that such a facility would cost about $50 billion (Bolgren 2007).

128 In today’s uranium market, the raw uranium going into a light water power reactor’s fuel assemblies represents only about 25% of their cost which, in turn, represents only 20-25% of the reactor’s total operational cost, most of which is the “overhead” required to support the people running/maintaining/overseeing it. Again, for such fuel about 80% of the raw uranium mined is discarded during its enrichment step and never ends up in a fuel assembly. Such “depleted” uranium is currently considered waste although a fraction of it is utilized to make military tank armor and ammunition.
by 2016 (CATO 2018). As of a year ago, assuming flat $350 million per year continued funding, they estimated that it would cost $17.2 billion and take until 2048 to complete (this sounds a lot like DOE’s predictions/promises having to do with its Hanford site’s waste “vitrification” project)\(^\text{129}\). In 2014, the Energy Department finally admitted that plutonium could be disposed of far more cheaply using a clever idea labeled “dilute and dispose” (patented?) but that notion was opposed by South Carolina’s political leadership headed by the redoubtable Lindsey Graham because it might kill what had become a very fat and dependable golden goose to his constituents. Consequently, from 2014 to 2016, Congress repeatedly gave DOE the same message: “keep building the MOX plant.” In 2017, Congress authorized energy secretary Perry to stop construction if he could show that another approach would cost under half that much. In May of 2018, DOE promised that if it were allowed to stop, that building’s shell could be converted to an equally or maybe even fatter “manufacturing plant for nuclear weapons”- type goose. As of May 2018, DOE was spending \(\sim\)$1.2 million per day studying its options (Judy 2018).

That batch of bomb grade plutonium isn’t “waste” because it cost US taxpayers many $billions to make and could serve as the start-up fuel for 4-15 full-sized breeder reactors\(^\text{130}\). This means that we should continue

\(^{129}\) At $17.2 billion, such fuel would be well over twice as costly as are today’s “mined uranium” \(^{235}\)U-based fuel assemblies.

\(^{130}\) Rumor has it that at least some of it is now being turned into fresh “pits” for the USA’s bomb inventory. Due to its multiplicity of allotropes, metallic plutonium tends to “age” meaning that such pits occasionally need maintenance or replacement.
to store it until it has been determined for sure which breeder concept represents the best way to implement a nuclear renaissance.

7.1.3 DOE Hanford’s reprocessing waste treatment project’s boondoggling

Some time ago another QUORA’s reader asked me, “Why do we continue to develop more nuclear energy and products when we cannot safely get rid of the radioactive waste?”

Like many of QUORA’s questions this one is somewhat misleading because the US is already implementing a perfectly reasonable way of dealing with that sort of “waste” – physically intact “spent” raw fuel assemblies generated by its civilian power reactors. That’s reasonable because, 1) it’s both safer and cheaper than is first reprocessing those assemblies and then dealing with the various radioactive waste streams so generated; and, 2) the MOX-type LWR fuel made from recycled plutonium isn’t worth what it costs to make. However, if the future’s decision makers were to decide to address mankind’s environmental and economic challenges with an appropriately scaled “nuclear renaissance”, they/we would have to switch to a closed nuclear fuel cycle capable of efficiently burning such stuff and resume spent fuel reprocessing (actinide recycling). Today’s set of self-defeating rules, laws, and assumptions render that rosy scenario impossible because they prevent the USA’s technical people from dealing with its already existing reprocessing wastes in a rational fashion which is, of course, exactly what the USA’s anti-nukes love to see – radwaste management has become a “transcientific”, not technical, problem. Unfortunately, it also provides the jobs supporting technical people, their management, contractors, and many “outside” advisors/helpers/officials/critics,
meaning that almost no one questions the paradigm driving Hanford’s radwaste boondoggling for over three decades.

The root cause of DOE Hanford’s Waste Treatment Plant’s (WTP) interminable cost overruns, delays, etc. (see Fig. 24)\(^\text{131}\), is that politically correct but technically unrealistic assumptions morphed into “promises” nearly impossible to keep. Its key technical assumptions - that Hanford’s tank wastes will be separated into “high” and “low” fractions so that the former can be dumped somewhere else and that both fractions will be converted to a borosilicate-type glass – don’t make sense for the following reasons:

- The ~55 million gallons of salt-wastes in Hanford’s tanks is extremely dilute radionuclide-wise and now old enough to generate relatively little heat which means that it is “high level” only due to its origin/history/associations\(^\text{132}\) (see APPENDIX IX)

- The probability that another US state would ever choose to host a repository for the “highest” stuff that might eventually be isolated from Hanford’s (Washington’s) waste tanks is low

\(^{131}\) Figure 24 was excerpted from slide set presented by a Washington state official nine years ago describing what had happened during the first 21 years of that project. At that time, Hanford was working on implementing its fourth official plan - it’s now working under its eighth official plan.

\(^{132}\) The AEC’s approach to fuel reprocessing stressed “productivity” and did not prioritize the minimization of ash forming additives (metal containing) which is the reason that the bulk of DOE’s HLW consists of non-radioactive sodium, potassium, aluminum, iron, etc., salts.
• Hanford’s tank waste is situated well above the water table in one of the USA’s driest deserts (it’s in a perfectly adequate but not “perfect” repository site)

• That site is already heavily contaminated – DOE’s hypothesized destination for Hanford’s “highest” stuff remains pristine almost four decades after ~15 billion tax dollars were wasted ”studying” it.

• The huge-scale radioisotope separations (aka “pretreatment”) required to isolate its waste’s especially “high” fractions are intrinsically difficult – mixing such stuff is easy/cheap, separating it (entropy reversal) is tough/expensive

• Pretreatment requires additional chemicals which would inevitably create still more radwaste,

• DOE’s one and only ”Vitrification and Privatization Success” (Pickett 1995) didn’t invoke pretreatment – everything in those particular radwaste tanks was simply mixed with powdered sand & borax and then vitrified (melted) to produce borosilicate-type glass “gems” (irregular obsidian pebble-like marbles)

• Hanford’s tank wastes contain large amounts of non-radioactive materials (e.g., sulfate and the halides) incompatible with the sort of glass (borosilicate) that its decision makers insist upon

• More suitable glasses have been extensively researched in the USA (Day 2005) and extensively employed elsewhere (Glagolenko 2005).

• Such glasses would be more chemically compatible with cementitious “grouts” (pumpable slurries that set up to form concrete) than is borosilicate glass.
Consequently, a more reasonable approach would be to mix, not separate, Hanford’s tanked radwastes and vitrify that mixture to make iron phosphate glass “gems” which would then serve as the aggregate of a cementitious grout pumped back into those same tanks for disposal.

Here’s why this proposal makes good sense:

- Hanford’s tanks (Fig.18) are neither evil nor apt to be going anywhere.
- They have already been paid for – the ~106,000 giant “transportable” (to where?) stainless steel canisters that the DOE’s current plans call for have not.
- Hanford’s much larger (typically 1 million gallon), steel-lined, reinforced concrete, underground “canisters” (tanks) (Figure 25) are apt to more durable over the eons than its current plan’s plastic-lined “not-high” radwaste disposal pits would be.
- Doing this would simultaneously remediate those tanks themselves - filling them with grout (concrete) would immobilize any residual waste, seal them, and render them both crush and corrosion resistant.
- It would obviate the current plan’s huge “interim” “high level” waste form packaging, storage, and (hypothesized) retrieval, repackaging, offsite transportation and disposal costs.
- It would be safer than the current plan because it’s a great deal simpler, meaning that “operators” wouldn’t have to do nearly as many things with/to that waste. Consequently, it would also be much, much, cheaper.

Figure 25: Hanford’s waste tanks during construction (typically 1 million gallon each).

Implementing my scheme with Hanford’s vitrified/grouted tank wastes would utilize under 30% of the space within its tanks because the glass would be more compact than the raw waste that went into it\(^\text{133}\). Since the Hanford site currently possesses many other sorts of radwastes (“crib” dirt, sludges, etc.) for which no solution has yet been implemented, most of them could and probably should be converted to the same sort of durable.

\(^{133}\)The reason for this is that such waste’s major components, both mass and volume wise, are thermally labile species such as nitrate, nitrite, and water which would not end up in any glass.
“aggregate” and grouted into those same tanks too. When that has been accomplished, it would then be reasonable to fill any remaining headspace with grout serving double-duty as a waste encapsulant for low-level “orphan” wastes\textsuperscript{134} imported from elsewhere.

When this scheme was presented to Hanford’s decision makers and their advisors six years ago (NWTRB 2013), I pointed out that they could probably levy substantial fees for providing such a noble service for other states and National Laboratories. I also mentioned that Congress may eventually decide to quit funding their giant boondoggle (~$59 billion at that time) which would eventually downsize everyone employed by it.

Hanford’s decision makers ignored me because, 1) they had already made too many silly assumptions, pronouncements, and promises based upon what the US federal government’s radioactive waste management experts had told them ~30 years before, and, 2) (more important) no sufficiently influential “outsider” was forcing them to shift their paradigm. That’s why its “vitrification” project hasn’t accomplished much other than reliably generate ~$2.5 billion/year worth of “work” for the horde of technical, legal, and bean counting experts struggling with their paradigm’s technical issues.

That project’s leadership and local stakeholders are apparently getting even more greedy/ambitious: recently (1Feb2019), the Hanford site’s local newspaper reported that, “\textit{The increase in costs for the tank waste treatment and disposition increases from an estimate of $53.5 billion in} “134 “Orphan wastes” don’t have a designated real or imaginary repository (home) yet.
2016 to a range of $221.4 billion to $518.1 billion in the report released Friday” (Cary 2019).

This country’s electorate’s docile acceptance of such self-serving nonsense from the people who nominally work for them is what’s turned most of their governments’ reprocessing waste management exercises into long festering boondoggles - Hanford’s just happens to be the biggest example of it.

Change may finally be at hand: On 18Mar2019, the Trump administration responded to Hanford’s request for still more money by cutting its budget by $416 million (from $2.5 to 2.1 billion)


7.1.4 DOE’s “lead nuclear engineering lab’s” radwaste boondoggling

The AEC/ERDA/DOE’s NRTS in Idaho had its own little fuel reprocessing facility to recover the highly-enriched uranium utilized in such testing so that it could be reused (about 50 different reactors were pilot-planted there from circa 1950 to the early 1970’s). ~90% of the liquid processing waste thusly generated was converted to a relatively stable/safe mix of dry dust and sand-like granules (“calcine”) which was and still is, stored within stainless steel tanks within reinforced concrete vaults (“binsets”). When the USA’s decision makers decided to end its nuclear fuel reprocessing activities, US DOE’s nuclear reactor R&D
pretty much ground to a halt too meaning that a “new mission” had to be found for its Idaho Site. Therefore, it eventually became DOE’s “lead laboratory in radioactive waste management” and was renamed the “Idaho National Environmental and Engineering Laboratory” (INEEL). Because the other DOE laboratories which had been running reprocessing facilities (Savannah River and Hanford) had already decided how their wastes were to be treated, INEEL’s new mission really just boiled down to devising “uniquely cost effective ways” of dealing with its own. The first priority would be its remaining ~1 million gallons of still-liquid “sodium bearing waste” (SBW) because it’s less stable and more mobile and therefore represents a greater threat to the good folks of Idaho than does its already-calcined stuff. Since INEEL’s calciner was still working at that time (1995), it would have been reasonable to simply add some sugar to its SBW, calcine it, and store it in its already built and paid for stainless steel/reinforced concrete “bin

Its most recent “old mission” had been to recover the remaining highly enriched uranium in spent naval PWR fuel. INEL’s “Chem Plant” had been almost totally refurbished to do so by the time that I “came on board” in 1978 – well over a billion 1970s-type dollars had been spent to build a new fuel dissolution system, fuel storage facility, and New Waste Calcination Facility (NWCF). Unfortunately, its dissolvers were designed to dissolve conventional zirconium (or “Zircalloy”) clad fuel assemblies – not the Navy’s “special” zirconium/uranium fuel assemblies alloyed (coated?) with the secret element that no one was allowed to mention. Anyway, it didn’t work very well and the Navy eventually decided to quit pounding money down DOE’s rathole. Uranium recycling is/was irrelevant to naval operations – it possesses cost-plus fuel contracts and the recovered uranium was not going to be reused in its own reactors anyway (it’s both too radioactive and 

Sugar serves as a chemical reductant for nitrate (or nitrite) and provides the carbon dioxide required to convert the resulting alkali metal oxides to relatively high-melting carbonates. This simultaneously prevents “bed agglomeration” and greatly reduces the amount of gaseous/toxic NOx generated (most of the nitrogen ends up as harmless N₂ instead). British and French reprocessing facilities sugar-calcine the wastes going into their HLW glass melters with close-coupled rotary kilns.
set number 7” until someone decides for sure what’s going to be done with INL’s calcines. That process had been developed and successfully pilot plant tested many times in the past. However, the folks who had previously managed the Idaho site’s reprocessing facility had become the leaders of its new waste management mission too, which meant that it was to be approached in the same fashion; i.e., calcines would be retrieved from their bins and dissolved in nitric acid so that most of their especially “high” radionuclides could be isolated and converted to hot isostatically pressed (HIPed) super-ceramic waste forms. In other words, an all-new facility would be built to “reprocess” calcine instead of spent reactor fuel and then convert the highest fractions so isolated into super durable, theoretically dense (maximally compact), radioactive waste forms. The rationale dreamed up for that brain storm was that, “the most problematic/expensive characteristic of INEEL’s anticipated reprocessing waste forms would be their physical volumes”; i.e., that there wouldn’t be enough “space” in DOE’s Yucca Mountain repository to accommodate INEEL’s reprocessing radwaste if its volume weren’t somehow reduced first. Of course, that really doesn’t make much sense because INEEL’s ~4500 m$^3$ of calcine could certainly have been fit into the ~370,000 m$^3$ of space (five miles worth of 25 ft.-diameter tunnels) that DOE’s YM study site’s tunnel boring machine had already created\textsuperscript{137}. However, DOE’s decision makers really liked that scenario... 

\textsuperscript{137} It was also inconsistent with the statute defining that hypothetical repository’s “capacity”; i.e., stuff containing radionuclides equivalent to that within 70,000 metric tons of spent ~33G WD/t power reactor fuel, not 70,000 (or any other number of) “cubic meters”. An independent evaluation of INL’s accumulation of calcines, spent fuel, etc. performed several years earlier had concluded that its HLW totaled up to an equivalent of about 320 tonnes of spent power reactor fuel (Rechard 1995). To make its brain storm appear more rational to its stakeholders, DOE decided to claim that each cubic meter of INL’s calcined radwaste is equivalent to 0.5 (not
because it was extremely complicated, meaning that lots of research would have to be done to work out its implementation details, which translated to job security for its field office personnel and their contractors’ favorite experts and managers. DOE’s decision makers would also be able to put off “final” decision-making (their job) until all of that research had been performed, properly reviewed, revised, and documented. Idaho’s most important stake holders also liked it because another couple decades worth of federal funding would be coming in to fund that/their terribly important “first of a kind” project.

Well, since SBW is/was already a nitric acid/nitrate salt solution containing some especially “high” components (TRU (transuranic elements), $^{90}$Sr, $^{137}$Cs, and $^{99}$Tc, it seemed to make sense to not calcine it as had been promised (Batt 1995) but instead save it to test the as-yet undeveloped separation technologies that were to be applied to its hypothetically redissolved calcines (this is a typical example of what DOE’s “road mapping” exercises accomplish). Consequently, its remaining liquid reprocessing waste never was calcined. When INEEL’s “outside” stakeholders finally realized that its separations-based waste management scheme didn’t make sense, its “waste side” contractor had

320/4500) m$^3$ of spent fuel and that the price that it’d be charging US taxpayers to store high stuff within its already bored-out YM repository would be ~$800,000/m$^3$.

$^{138}$ Everyone working for DOE in one way or another (civil service, contractor/subcontractor personnel, and the academics it chooses to fund) is rewarded for doing/saying things consistent with its current thinking. Consequently, during those times when its leadership apparently isn’t interested in actually solving problems (e.g., while INEL/INEEL was DOE’s lead lab in radioactive waste management), coming up with a fresh excuse for not solving them is career enhancing.
had already permanently shut down its calciner and the deadline to complete the “treatment” of its SBW was now only about 11 years off (i.e., to be completed by 31Dec2012 – the deadline for completing calcine treatment/disposal was and is still 31Dec2035). This sparked a renewal of the waste vitrification (glass-making) research that had been limping along during most of the previous three decades (EIS 2002). However, that option also vanished when in late 2002, DOE’s brand new “EM-1” (Jesse Roberson) declared that vitrification would be “too expensive” for INEEL (but still OK for both Savannah River and Hanford – she’d apparently already been traumatized by the latter’s “vit plant” boondoggling). Consequently, INEEL’s decision makers had to look for something else that would be uniquely cost effective. Ignoring several “outsiders” and one insider’s advice (mine – Siemer 2005), they settled upon “steam reformation” because it invoked a mysterious (“proprietary” therefore perfectly OK for both DOE and its contractors to keep secret) but apparently successfully patented, fluidized bed-based “steam reforming” technology rather similar to the calcination that

139 The rationale ginned up for shutting down INEEL’s calciner (NWCF) was that because it was a waste “incinerator” it would have to be rendered MACT compatible (i.e., modified so that it not emit a huge cloud of NOx) which, in turn, would “cost taxpayers too much” (~$50 million). What wasn’t mentioned were that; 1) calcination isn’t incineration because the waste in question isn’t flammable, 2) sugar calcination would have greatly reduced NOx emissions, and 3) calcination could have been completed well before the EPA’s MACT compliance deadline (June 19, 2001, see EPA 1998).

140 “DOE-ID should not pursue further steam-reforming initiatives for treatment of SBW to produce waste forms for direct disposal in a federal HLW repository or in WIPP ” (Gentilucci et al. 2001)

141 Steam doesn’t “reform” anything other than some of the solid carbon (instead of dissolved sugar) serving as the reductant in that sub contractor’s (THOR’s) proprietary technology (i.e., C+H2O →CO+CO2+CH4+H2 etc.). Unfortunately, much of that reductant (generally coal) is
INEEL’s managers and engineers were already comfortable with. Other pluses were that the subcontractor in question claimed that its process could make a variety of products suitable for any sort of repository anywhere, and that it would only cost about $45 million\(^\text{142}\) to treat INEEL’s SBW.

APPENDIX IVX describes the steam reforming process and explains how it came to be DOE’s “preferred alternative”.

This story is already getting too long, but suffice it to say that: 1) circa 2006, DOE decided that steam reforming’s easiest-to-make (and least durable; i.e., water soluble) “carbonate product” would be good enough for its not-so-high-level repository site\(^\text{143}\); 2) all attempts to get even that relatively simple process actually running have since failed; 3) 100% of INL’s liquid reprocessing waste remains in its tanks over six years past DOE’s promised 31Dec2012 treatment and disposal deadline; and, 4) simply blown up and out of the >>600°C reactor along with the other “fines” which collectively constitute the bulk of its product. In principle, but not in practice (too problematic), it is possible to convert SBW’s ash-forming elements (mostly sodium, potassium & aluminum) to a more durable (not as water soluble) nepheline-like, alkali aluminosilicate mineral assemblage by adding some clay too (Siemer 2005).

\(^{142}\) That’s the figure quoted to me by the STUDSVIK expert that eventually became THORTT’s chief technical expert when I first explained INEEL’s SBW treatment problem to him circa October 1997 asking him to remind my bosses that fluidize bed sugar calcination had also worked for the subcontractor he was then working for (VECTRA) to pretreat Hanford’s radwastes for subsequent vitrification (VECTRA GSI Report #. WHC-VIT-03).

\(^{143}\) i.e., the Waste Isolation Pilot Plant (WIPP). That decision was likely due to the fact that none of the “demonstrations” of the sub contractor’s (THOR’s) attempts to make the superior (not so water soluble) product specified for DOE’s HLV (YM) repository had worked as had been repeatedly claimed. That information was only released to me via a freedom of information request (Hazen 2007) – up until then, the “raw” data/reports generated by its subcontractor’s (Hazen’s) tests/demonstrations had been kept under wraps due to their “proprietary” nature.
INL’s still-continuing steam reforming boondoggling has probably already cost US taxpayers well over a billion dollars (more exact cost figures are unavailable to “outsiders”).

In the DOE Complex, “troubleshooters” are ignored because there is no reason not to: programmatic waste, fraud, abuse and failure has become the norm for its nuclear-related projects and the only thing that really counts with regard to individual personal career development is being an organized good team player. Also, in every case I’ve seen & tested (several times), the outside stakeholders that really count (politicians) aren’t much interested in anything beyond maintaining local spending & employment figures.

The worst news is that circa 2005 INEEL was reacronymed “INL” and its leadership given a new and much more important mission to manage

\[\text{\textsuperscript{144}}\] Another reason is that DOE’s program managers don’t take responsibility for any sort of technical goof and are rarely punished for failure (contractors get the blame). The same applies to the management of the institutions nominally responsible for overseeing its activities. In the DOE Complex, no one seems to be responsible for anything other than complying with rules and procedures. If program oversight doesn’t mean accountability, it doesn’t mean anything. That’s totally counter to Rickover’s management philosophy: “You may delegate it, but it is still with you... If responsibility is rightfully yours, no evasion, or ignorance or passing the blame can shift the burden to someone else. Unless you can point your finger at the man who is responsible when something goes wrong, then you have never had anyone really responsible. “

\[\text{\textsuperscript{145}}\] I have yet to hear back from any of the politicians & officials to whom I’ve sent letters (e.g., APPENDICES VII & VIII).

\[\text{\textsuperscript{146}}\] The fact that DOE’s locally important political stakeholders routinely agree to project completion dates ridiculously far off in the future supports this probably “controversial” contention. If in 1995, Idaho’s Governor Batt had given DOE, let’s say, five years to complete the calcination of INEEL’s reprocessing wastes, that’s what would have happened. Allowing DOE 17 years to accomplish something that could/should have easily been done within two years effectively issued it & its contractors licenses to steal.
– it became DOE’s “lead nuclear engineering laboratory” and has remained so to the present.

Its NE R&D projects have failed to accomplish its new mission for the same reason that its signature technical waste management project (SBW “treatment”) did – its managers neither motivate nor empower its scientists and engineers to do what’s necessary to succeed.

I’m not alone in having that opinion. “A Retrospective Analysis of Funding and Focus in US Advanced Fission Innovation” jointly funded by the John D. and Catherine T. MacArthur Foundation and six other agencies independent of the US DOE (Abdulla 2017) concluded that, “Using extensive data acquired through the Freedom of Information Act, we reconstruct the budget history of the Department of Energy’s program to develop advanced, non-light water nuclear reactors. Our analysis shows that—despite spending $2 billion since the late 1990s—no advanced design is ready for deployment. Even if the program had been well designed, it still would have been insufficient to demonstrate even one non-light water technology. It has violated much of the wisdom about the effective execution of innovative programs: annual funding varies fourfold, priorities are ephemeral, incumbent technologies and fuels are prized over innovation, and infrastructure spending consumes half the budget. Absent substantial changes, the possibility of US-designed advanced reactors playing a role in decarbonization by mid-century is low.

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147 Abdulla et al had to sort through a 400,000 page FOIA data dump to come up with the numbers leading to their conclusions (Abdulla 2017 – read it, it’s “open access”).
Another paper published that same year, “Expert Assessments of the State of U.S. Advanced Fission Innovation” (Ford 2017) concluded that “.... results from structured interviews conducted with 30 nuclear energy veterans to elicit their impressions of the state of U.S. fission innovation. Most experts assessed NE as having been largely unsuccessful in enabling the development of advanced designs. The interview results highlight the importance of leadership and programmatic discipline, and how their absence leads to poor performance in driving change. Responses point to the likely demise of nuclear power and nuclear science in the U.S. without significant improvements in leadership, focus and political support.”

Amen.

7.2 Fukushima’s “nuclear disaster”

In 2011, an eminently predictable earthquake and subsequent tsunami off the east coast of Japan did about $300 billion worth of property damage and killed about 9,000 people. Nevertheless, about the only thing that we hear about is the Fukushima Daiichi nuclear power plant’s “nuclear disaster” which killed no one and damaged only that facility’s equipment and buildings. Several days after its reactors had been safely shut down, the cooling water in three of them and some adjoining fuel assembly storage tanks boiled away after which that

148 Two people did drown there when the tsunami initially flooded the site.

149 The removal of fission product decay heat is a key feature of any reactor’s primary cooling system. When the reactor’s chain reaction stops for any reason (it is no longer “critical”), fission product decay continues to generate a substantial amount of heat energy. At the moment of shutdown, it amounts to about 6.5% of the reactor’s full power rating, but drops to about 1.5% within an hour. After a day, it’s fallen to 0.4%, and after a week it’s only about 0.2%. Nevertheless, cumulatively that’s enough heat to melt the fuel assemblies unless it is safely
fuel’s zircalloy cladding became hot enough to melt, react with steam and generate hydrogen gas which accumulated at the tops of several tightly sealed buildings and subsequently exploded. Those chemical—not nuclear—explosions didn’t actually injure anyone but them along with the fact that some of the fuel itself melted down prompted Japan’s authorities to grossly over-react\textsuperscript{150} thereby causing panic, confusion, ~1600 additional deaths, and even more property losses.

As is also the case in most Western countries, any sort of “nuclear” incident causes Japan’s authorities to act like frightened chickens. Due to the consequences of that behavior, many Japanese people have completely lost faith in TEPCO, their government, and the clean power source responsible for much of their nation’s economic success. Fukushima’s people are suffering not just from the earthquake and tsunami, but also from extreme anxiety (“radiophobia”) which generates stress and suppresses their immune systems.

One reason why that power plant’s fate constitutes a genuine disaster is that Japan’s economy will continue to suffer economic fallout estimated

\textsuperscript{150} “Over reacted” means that many of the official decrees negatively impacting Japanese peoples’ lives and livelihoods were absolutely unnecessary – see this chapter’s next sections. The only thing that really needed to happen rad-wise was for those authorities to assure that the locals consumed a total of roughly one gram (less for infants) of sodium or potassium iodide during the first month after the tsunami (Verger 2001). Some of their actions suggest that they believed that radioactive atoms are like pathogenic microorganisms; i.e., a trace of contamination might multiply within its victim rendering him/her a potential “carrier” of something deadly that other people might catch.
to eventually reach one trillion USD. That money will go to pay for cleanup, the additional high-priced imported fossil fuels that they will continue to have to pay for, loss of economic productivity, insurance claims, lawsuits and addressing stress-related health issues (including suicides) engendered by forced dislocation and fear mongering.

Japan will not meet its greenhouse gas emission reduction targets and will become more polluted because it’ll burn more coal and other fossil fuels to generate electricity. Because coal concentrates natural radionuclides, it's likely that the average Japanese person will be exposed to slightly more radioactivity than when all of their nuclear plants were running.

Japan will move to renewables more quickly than planned and, because its feed in tariff for them is high, that will also raise its citizen’s electricity costs.

World-wide, “Fukushima” has been an even bigger disaster because it’s caused many of the world’s decision makers to swear off nuclear power. If the inevitable strife ensuing when a “no-nuke” future world’s oil/gas becomes too expensive sets off a “WW III”, it might prove to be the “incident” that sparked the end of modern civilization.

The root causes of Fukushima’s dismal fate are the same human factors responsible for most of the other “issues” that have prompted widespread distrust of nuclear power. In Fukushima’s case, human

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151 There is a point beyond which power and pride cannot back down regardless of cost. As people like some of today’s world leaders become more and more invested in a situation, they themselves lose the freedom to choose alternatives and march their subjects off into hell. That’s how both of mankind’s prior “world wars” started.
nature first manifested itself in reactor siting. GOOGLE EARTH reveals that the Fukushima Daiichi industrial complex occupies a roughly one square mile parcel of coastland ranging in altitude from 10 to about 40 meters above sea level. Its reactors and their attendant spent fuel storage buildings occupy roughly 10% of that area and are all situated along the coast line where the ground is currently only about 10 meters above sea level – ancillary buildings etc., are situated on the shallow “hill” behind them. Since the tsunami that wrecked everything was “only” about 13 meters high, one of the ways that that disaster could have been averted would have been to simply site its reactors upon that parcel’s higher areas rather than immediately next to the ocean. Another would have been to build a higher sea wall.

Documents filed with Japanese authorities in 1967, show that when TEPCO (the electrical utility owning that facility) was planning its new nuclear power plant, it decided to deliberately lower the site’s natural, 35-meter high “seawall” (cliff) to just ten meters which, of course rendered the power plant subsequently built upon it vulnerable to the 13 meter tsunami that struck it in March 2011. A former TEPCO executive who had been part of that decision making team explained that it was based upon two considerations. One, that reducing that site’s natural cliff wall’s height by 25 meters would render delivering equipment to it much easier (equipment which was mostly delivered by sea – a full sized LWR’s Rankine-type turbo generators weigh about 500 tonnes); and, two, that it would be somewhat easier/cheaper to access the seawater which would be cooling its reactors from 10 meters above sea level rather than 35. In 1991 the U.S.A’s Nuclear Regulatory Commission warned Japan’s decision makers of a risk to that site’s losing its emergency power system (its big/heavy backup diesel-powered pumps were situated in basements where they could be readily flooded) and Japan’s own “Nuclear and Industrial Safety Agency” (NISA)
subsequently reminded them of that again in 2004. Also in 2004, two more of Japan’s governmental oversight committees issued warnings that tsunamis over twice the height assumed by TEPCO’s planners circa 1967 (5.7 meters) were possible. In response to the Indian Ocean tsunami, during 2006 and 2008 two TEPCO-employee (in house) studies investigated the effects of tsunami-waves higher than their facility’s "official" (design basis) wave height upon its performance. The 2006 simulation’s conclusions were that a 13.5 meter wave would cause a complete loss of all power and render it impossible to inject water into reactor No.5 and that the costs of protecting the plant from them would be about 25 million dollars (under 0.01% of what Japan’s ministry of trade, and industry ministry subsequently declared (in 2016) that dealing with the subsequent disaster would end up costing). The 2008 study assumed a more moderate 10 meter high tsunami. In both cases TEPCO failed to act because its decision makers considered those studies to be training exercises for junior technical employees and neither they nor their apparently “captured” regulators really expected such large tsunamis.

The similarly-designed/sited Fukushima Daini nuclear power plant seven miles south of it was also successfully shut down and suffered virtually no damage largely because one of the “outside” power lines to it had survived the tsunami.

That fiasco generated plenty of opportunities for fear mongers to scare people about Fukushima’s “deadly radiation”. The goal sought and often attained by such mongering is to scare innumerate (normal) people with big technical-sounding numbers and acronyms. For example, a recent
Dailykos posting’s really big scary number is that “some of the tuna caught near Japan had up to 1000 Bq\textsuperscript{152}/kg of deadly \textsuperscript{137}Cs in them”.

Let’s look at that FUD quantitatively assuming a victim both rich and dumb enough to eat nothing but Japanese tuna; i.e., those fish most exposed to the Fukushima reactors’ “terribly radioactive” drainage. Let’s also assume that that person weighs 70 kg and needs about 2000 kCal per day to keep body & soul together.

Since 3.5 oz. of tuna has about 200 kCal, he’d/she’d have to eat about 362 kilograms of it every year.

That’s a tuna consumption rate of 1.15E-5 kg/sec which at 1000 Bq/kg equates to 0.0115 Bq of \textsuperscript{137}Cs consumed per second.

According to the radiation decay equation (see APPENDIX XI), that corresponds to consuming 1.58E+7 [0.0115*3600*24*3600/ln2] \textsuperscript{137}Cs atoms/sec.

Over a year, that’d be an accumulation of 4.98E+14 \textsuperscript{137}Cs atoms if 100% of ‘em “stuck”. However they wouldn’t stick because Cs has a biological half-life of ~70 days (less if one drinks lots of beer) which means that ~0.27% (0.5^(365/70)) of the \textsuperscript{137}Cs atoms consumed would actually contribute to his/her rad dose— that’s an average of 1.34E+13 “evil” atoms decaying away within our hypothetical maximally exposed victim.

\textsuperscript{152} Bq (one of the smaller measures of radioactivity in common use) = 1 decay“event” per second = 1 d/s = 1 dps. One “Curie”, another common unit, = 3.7E+10 Bq. An expert that really wants to scare you, might express radioactivity in terms of pico or fempto curies (the potassium within an average-sized banana subjects anyone eating it to ~ 600,000 fempto curies worth of beta-type radiation for several weeks!! A can of beer is only about one fourth that deadly.)
The radiation decay equation equates that many $^{137}$Cs atoms to a decay rate of 97,900 disintegrations per second (Bq) throughout that year.

Since each $^{137}$Cs decay generates about $1.1 \text{ Mev} \& 1 \text{ ev} = 1.6E-19 \text{ J}$, that’s a whole body dose of $0.0544 \text{ J/year}$ which in a 70 kg body comes to a dose of $0.0077 \text{ J/kg (Sievert)}$ \[97000*1.1E+6*1.6E-19/70].

The average US Citizen gets about 0.0062 Sievert’s worth of radiation per year – more if he/she lives in an especially dangerous place like western Colorado or spends much time jet-setting or mountain climbing.

Consequently, our extremely rich (that much tuna would cost ~10x an average Japanese citizen’s disposable income) & maximally-exposed victim would be getting about the same dose from it that average US citizens normally receive from the part of this world that they live in.

### 7.3 The nuclear industry’s LNT-based radiation dose assumptions

The “technical” rationale underlying both the USA’s radwaste boondoggling and Japan’s response to TEPCO’s travails is that the international body responsible for setting radiation dose recommendations (ICRP) utilizes an overly simplistic linear dose effect model assumption to predict the effects of vanishing small radiation exposures upon living creatures. That model’s acronym is LNT which means linear-no-threshold. Its principle was introduced in the late 1950s and remains the basis for dose limits recommended everywhere because it’s both politically correct and conservative. Back in the 1950s a “target theory” dominated the evaluation of radiation data. It was assumed that the biological impact/result was due to a “hit” – and the number of hits does indeed increase linearly with dose. A few years later it was also
accepted that the initial step for carcinogenesis (cancer’s initiation) is damage to a cell’s DNA. Again, the initial number of DNA-damages does increase linearly with dose. Thusly as long as our experts and authorities choose to ignore the defense and repair mechanisms possessed by any/all of the Earth’s real-world biological systems, it’s not unreasonable (conservative) to assume the LNT-model. It’s especially useful to anyone seeking to frighten people or rationalize additional personnel expenditures (more “health physicists”) and/or super-profitable radwaste boondoggling.

The fact is that there are dose thresholds below which the cell repair mechanisms protecting us from the free radical damage caused by the fact that we eat food and breathe a reactive gas (oxygen) also protect us from the free radicals generated by low dose rate ionizing radiation (certainly anything under about ten times above normal background). That’s why the nuclear industry’s workers live at least as long (actually longer) than do those of most other professions, and there have been no massive die offs after the initial effects of Hiroshima’s bombing, the USA’s atmospheric bomb testing, or even big screw-ups like Fukushima’s have dissipated.

For example, in the southwest Indian state of Kerala, despite background radiation levels about 30 times the global average, children under five have the lowest mortality rate in that country and an average life expectancy of 74 (Kerala 2015).

For thousands of years, Keralites have lived with background radiation levels three times that which triggered the evacuation at Fukushima, where the limit was (on July, 2016) 20 mSv/yr - the same figure permitted for most of the world’s professional radiation workers. In contrast, sections of Kerala experience an average of 70 mSv/yr, with some areas as high as 500 mSv/yr and their locally grown food averages
about five times as radioactive as is that consumed in the United States. Despite its high background levels, Kerala’s cancer incidence is the same as that of greater India, about one-half that of Japan’s and under a third that of Australia’s. As the linked article says, “Cancer experts know a great deal about the drivers of these huge differences, and radiation isn’t on the list.”

A similar situation obtains in Ramsar, a city in northern Iran, whose citizens have received an annual background radiation dose of up to 260 mSv/y for many generations – that’s 13 times higher than that which triggered the expropriation of ~100,000 of the Fukushima Prefecture’s citizens’ homes, farms, and businesses by their government. Here’s part of the ABSTRACT of a paper describing how Ramsar’s elevated background radiation impacts its people’s health (Ghiassi-nejad 2002)

“Cytogenetic studies show no significant differences between people in the high background compared to people in normal background areas. An in vitro challenge dose of 1.5 Gy of gamma rays was administered to the lymphocytes, which showed significantly reduced frequency for chromosome aberrations of people living in high background compared to those in normal background areas in and near Ramsar. Specifically, inhabitants of high background radiation areas had about 56% the average number of induced chromosomal abnormalities of normal background radiation area inhabitants following this exposure. This suggests that adaptive response might be induced by chronic exposure to natural background radiation as opposed to acute exposure to higher (tens of mGy) levels of radiation in the laboratory. There were no differences in laboratory tests of the immune systems, and no noted differences in hematological alterations between these two groups of people.”

Note that this study’s authors observed the same effect that other such studies noted; i.e., that modestly elevated radiation levels seem to strengthen human immune systems akin to the way that physical exercise does.
The USA’s hyperconservative approach to establishing radiation guide lines impacts many of its citizens too. For instance, an abandoned elemental phosphorus plant situated ten miles west of Pocatello ID is shadowed by a roughly 30 million tonne mountain of phosphate rock slag that the EPA has deemed too radioactive to utilize for any constructive purpose. Prior to that decision it had been widely used for road and parking lot construction, construction fill, railroad ballast, home foundations, driveways, and even built-up-type roofing materials. The “alarm level” imposed upon the people owning, living in, or trying to sell such property (20 mrem/hr or 0.00175 Sievert/a) represents just ~25% of the radiation dose that an average American citizen gets from everything else he/she does (Gesell 2013).

This is just another manifestation of human nature, i.e., that especially “important” people desire to remain important. It is the reason that when agencies established to address certain obvious safety issues have succeeded in that mission, their leadership tends to keep ratcheting up criteria in order to keep their jobs/agencies relevant. For instance when I and my fellow analytical research chemists during the 1970s and 1980s, made it possible to detect hazardous substances (in my case toxic metals via graphite furnace atomic absorption spectrometry) at progressively lower concentrations in foods, water, or the “environment”, the statutory limits for such things tended to drift in the same direction, “to provide an extra margin of safety” (and of course to keep the regulators, inspectors, and analysts busy). This tendency often goes well beyond reasonable
levels and thereby generates a great deal of anxiety, and, in the case of radionuclides, waste, fraud, and taxpayer-abuse\textsuperscript{153}.

There are a number of other well-written papers and books freely available to anyone wishing to learn more about this subject (Henriksen 2015, Calabrese 2013, Cutler 2014, Scott 2019).

The elements responsible for most of our background radiation (uranium, thorium, and potassium) render “advanced” life possible on Earth because they generate the heat necessary for two of its unique features: plate tectonics and a still molten and therefore magnetic iron/nickel core (Ward and Brownlee 2000).

7.4 ALARA (As Low Reasonably Achievable)

ALARA is another fine-sounding principle that’s served to cripple the nuclear industry, especially anyone working for/at the USA’s national laboratories\textsuperscript{154}. In practice, the “reasonably” part of that acronym is

\textsuperscript{153} The same sort of bureaucratic overreach has also officially rendered a good deal of the USA’s drinking water “unsafe” because a substantial fraction of its groundwater contains enough arsenic to exceed the EPA’s 10 ppb (part per billion) limit – prior to 2001 that limit had been 50 ppb. Affected regions include Southwestern states like Nevada, to the upper Midwest and New England, where a belt of arsenic-infused bedrock taints aquifers in stretches from the coast of Maine to a point midway through Massachusetts. The studies serving to rationalize that hugely impacting (too expensive) ruling were performed in Bangladesh where well water arsenic levels are typically higher than 50 ppb, and more importantly, such water is used to irrigate a single crop (rice) constituting its citizen’s and their domesticated animals staple food under conditions uniquely well suited for its uptake (rice paddies). The people genuinely affected by that problem are too poor to quit raising rice – the USA’s citizens are not so poor and have far more varied diets.

\textsuperscript{154} Since DOE’s laboratories don’t have to actually produce anything other than “reports” there’s no real-world pressure upon them to do anything quickly and efficiently. To the contrary, foot dragging keeps their missions alive which, in turn, keeps the study-money coming in.
ignored which means that it really says that there are no limits below which additional expenditures/efforts/training to further reduce personnel radiation exposures aren’t always “worth it”. That principle tacitly assumes both that the LNT hypothesis is correct and that the nuclear industry and its helpers will always have cost plus contracts and hence never face serious competition regardless of how much additional overhead costs they choose to assume. Neither assumption is correct. Since the “safest” way to work with anything that’s radioactive, is to not work with anything that’s radioactive, the DOE nuclear complex’s leaders have replaced most of its hot laboratories/pilot plants along with the people that had worked in them with computerized modeling/modelers thereby rendering their laboratories incapable of doing the real world experimentation required to develop anything genuinely new.

“The country needs and unless I mistake its temper, the country demands bold persistent experimentation. It is common sense to take a method and try it. If it fails admit it frankly and try another. But above all try something”. Franklin D. Roosevelt.

The main reason that many people fear radiation is a deeply rooted psychological fear of mysterious entities that can’t be seen or touched (e.g., Blair-type witches and voodoo)\(^{155}\). Such fears were originally

\(^{155}\) During the last millennium, roughly a million certified “witches” were executed because they could not prove that they had not caused harm to someone or something. In the same way, since one cannot prove that tiny amounts of radiation did not cause a particular leukemia—for that matter one cannot prove that they caused it either—those who wish to succumb to low-level phobia do so, those who don’t wish to do so, don’t. On the other hand, very few people fear the smoke emitted by burning some fossil fuels and most sorts of biomass currently responsible for about 7 million deaths per year. Consequently, James Hansen has estimated that nuclear power has thereby already saved about 2 million human lives (Silva 2013, WHO 2018).
engineered into our ancestors’ more primitive brains on the African savannah millions of years ago to make them safer from predators at night. However, we’re not quite so primitive now and should know better than that: we’ve all seen images of the mangled and burned bodies caused by car accidents, yet we continue to embrace automobiles because such risk is considered worth taking because we have trained both ourselves and our children to distinguish between rational expectations and gut feelings. We must to become willing to do the same with nuclear power, especially with new reactors featuring improved safety, lower costs, and greater efficiencies.\(^{156}\)

### 7.5 Over blown proliferation concerns

Many of the West’s nuclear decision makers refuse to consider anything that might lead to greater “proliferation risk”. For instance, they might say that, “your reactor concept/scenario is impossible because its fissile isn’t ‘denatured’\(^{157}\) enough.”

That assertion makes about as much sense as claiming that it would be impossible to revive the USA’s space exploration program because its decision makers would prefer that NASA’s technical initiatives be powered with conservation. First, since it tacitly assumes that any new reactors would be subject to the same set of arbitrary (and apparently immutable) man-made rules as are today’s, it also tacitly assumes that

\(^{156}\)“Nothing in life is to be feared, it is only to be understood. Now is the time to understand more so that we can fear less” Marie Curie.

\(^{157}\)Denatured means that the actinide isotope(s) constituting its fissile (e.g. \(^{235}\)U) is diluted with enough of that element’s non fissionable isotope (s) (e.g., \(^{238}\)U) that it would be impossible for imaginary terrorists to make a bomb of “diverted” reactor fuel unless they were also able to “enrich” it. The degree of dilution required is <20\% for \(^{235}\)U and <12\% for \(^{233}\)U.
the world will always need the uranium enrichment facilities that represent a far greater proliferation threat than does the fissile material within any nuclear reactor. Second, diluting (“denaturing”) the $^{233}$U in, let’s say, the MSFR or LFTR’s salt streams with ~8x as much $^{238}$U would: 1) render its fuel cycle unsustainable and therefore obviate the main reason for implementing any sort of nuclear renaissance; 2) greatly complicate that reactor’s operation thereby increasing its electricity’s cost (and, likely also, its operators’ radiation exposures); and 3) turn that resulting converter-type reactor into just another large-scale transuranic radwaste (plutonium etc.) maker. It’s also hypocritical because the US federal government – a signator and vociferous proponent of the Nuclear Non-Proliferation Treaty – has been operating many HEU-fueled (naval) reactors for over a half century and is likely to continue to do so. There have been no “diversions” of their bomb grade fissile by terrorists and it’s unrealistic to assume that any within a power reactor sited within any first world country would be either.

Any uranium-fueled reactor breeds at least some plutonium$^{158}$ which could in principle be recovered and perhaps – if it’s >90% $^{239}$Pu, not reactor grade plutonium – could become the “pit” of a nuclear weapon. Some folks therefore claim that any sort of fuel “reprocessing” (an absolute necessity for any sort of genuinely sustainable nuclear fuel cycle) would dramatically increase the risk of nuclear war. It’s true that it’s “possible” but is also very much less likely than, let’s say, runaway global warming due to our refusal to stop such dithering or North Korea’s (which has no power reactors) leadership’s deciding to nuke

$^{158}$ About 40% of a typical uranium-fueled LWR’s heat energy is generated by in-situ generated/burned $^{239}$Pu.
US military bases in South Korea and Japan. Choosing to develop a nuclear arsenal is a political decision, not a technological imperative. All of today’s technologically advanced nations are capable of developing/building nuclear weapons if they choose to do so. There are about 40 such nations in the world today and only nine of them have built/maintain nuclear arsenals. The others chose not to do so and most have signed a solemn treaty to that effect. Nations and people don’t have to act stupidly and/or selfishly – they choose to do so159.

Chapter 8. “The Damned Human Race” (Twain 1909)

The biggest barriers to implementing my scenario’s technological fixes are posed by human, not “mother”, nature. Unlike the “controlled fusion” will-o-the-wisp that has dominated DOE’s nuclear reactor development efforts/funding for several decades, there is almost no doubt that a sustainable molten salt fission-type reactor could actually be built. The USA simply hasn’t been willing to do the real world experimentation required to work out that scenario’s implementation details.

Solving the tough technical problems posed by the natural world’s rules requires intellectual honesty – seeking Nature’s opinion regardless of

159 For instance, North Korea, a poor nation refused admission into the “nuclear energy club”, built its own tiny (5 MW) “production” reactor to make plutonium bomb pits with. The much richer South Korea generated several thousand times as much nuclear energy to power its economy but refused to make bombs.
whether or not it agrees with yours, your peer group’s or your boss’s personal beliefs. It’s about finding reasonable solutions, not winning arguments or pleasing the people that fund you. It’s also sometimes hard and even somewhat “risky” work. To many of the people who’ve chosen to become scientists & engineers, doing such work also happens to be a great deal of fun\textsuperscript{160}.

For success to happen, R&D workplace managers must foster a culture where everyone can:

- Feel safe to speak up
- Express alternative points of view
- Challenge the status-quo and/or their bosses
- Acknowledge mistakes without fearing punishment

Unfortunately, that would require those leaders to embrace vulnerability, which is much easier said than done. It’s tough for the most “important” people within any organization to let go of their need to be, and, equally important, to always have been\textsuperscript{161}, “right” about everything. Decisions should be grounded upon facts, not schedules or the stature, position, or history of individuals working on the problem.

\textsuperscript{160} With a few exceptions I don’t miss the people that I worked with at INL but do miss my lab (it’s been “decommissioned” along with almost all of INL’s other nominally hot labs). To people like me, a well stocked laboratory is a wonderful playground. \textit{“Happiness lies in the joy of achievement and the thrill of creative effort.”} Franklin D. Roosevelt.

\textsuperscript{161} This is one of the reasons why institutions rarely start over from scratch when projects like this book’s examples of boondoggling have repeatedly failed – doing so is a tacit admission that that their leadership’s approach to decision making is flawed. Lower ranking people just keep pretending that their emperor’s new clothes continue to be as beautiful as they were at first sight.
System justification theory (SJT) explains why people within large groups often act/vote in ways that are directly contrary to their own self-interests. It points out that system-justifying beliefs serve a psychologically palliative function to many people even when the system in question is disadvantageous to them. It’s responsible for the counter-intuitive behavior often seen in oppressed (“low-status”) groups, wherein they buy into their oppressors’ propaganda.162

According to SJT, humans have three competing psychological motives: ego motive, group motive, and system justification. Our ego says, “I like me.” The group motive makes us say, “I like us” (and, conversely, “I don’t like them”). However, the system justification motive causes us to believe that, “I like things the way they are.” Sometimes these motivations reinforce and sometimes they compete, depending upon circumstances.

System justification embodies our desire to believe that the world is logical (makes good sense) - that things are the way that they are for a damn good reason (God? the Constitution?). It is why many low-status people within a culture often defend the privileges and sometimes grossly inappropriate behavior of its high-status people. Further, it explains why if disadvantaged members of a group are not having their ego or group justification needs met, they will actually be less likely to demand societal/cultural changes. They rationalize163 their position

162 An example of such individuals would be the majority of Mr. Trumps voting “base”.

163 When I was a kid, my chief hero was Isaac Asimov closely followed by Robert Heinlein. It was fascinating but not too surprising to recently learn that Heinlein had characterized us humans as rationalizing, not rational creatures.
within it, and internalize a belief that they deserve to be in their current position (*I’m just a chemist, who am I to question what the Chem Plant’s managers want to do?). Of course, the advantaged members of such groups have an even more “conservative” view of the world: “*things are right as they are*”. Consequently, to them, everything is simple: just set up the rules and structures (“procedures”) to be blind to individual characteristics, and the system will assure that everything will work out fine with everyone having a “fair and balanced” shot at achieving happiness and success. In such a culture, if anyone happens to fail, it's due to a flaw in their personalities, not the system itself\(^{164}\). In many ways, conservatives see “systems” to be the most important thing which is why the leaders of political parties, corporations, and institutions behave the way they do.

The examples I’ve already described reflect several of human nature’s less admirable characteristics including…

### 8.1 Greed:

Doing the right things at Fukushima would have cost a bit more and thereby reduce profit margins. Doing the wrong things with Hanford, INL, and SRLs’ reprocessing waste increased profit margins by making more “work”. In cost-plus government contracting, no mole hill is too

\(^{164}\) That’s why it’s so easy to brush off the complaints of such losers by simply calling them “disgruntled employees”. I suspect that some of the Jews sent to Auschwitz were also disgruntled.
small to become a mountain if the people authorized to climb it choose to pretend that it is and no one challenges them\textsuperscript{165}.

The first thing that everyone facing a “new” technical problem should do is to familiarize themselves with what’s already been done to deal with similar problems. Most of the world’s technical issues already have perfectly reasonable solutions – what’s been lacking is the collective will to recognize that fact and thereby actually address the problem. One of the reasons for this is that most of the people assigned to deal with them are either in the “research” (study) business (most of the scientists and engineers) or don’t want to “rock the boat” (upset people) any more than they absolutely have to (most politicians and governmental program managers). Both of those human characteristics incentivize “experts” to ignore what should be obvious solutions and, instead, turn every new “technical” mole hill into a mountain requiring the performance of a great deal of cutting-edge research before any serious changes have to happen. That’s the reason that the US Department of Energy’s “legacy” reprocessing waste treatment efforts at both its Idaho and Hanford sites’ morphed into the interminable multibillion dollar “study” boondoggles mentioned in this book.

Organized (usually corporate sponsored) greed seems to have become especially pernicious. Acquisitiveness is the chief driver for

\textsuperscript{165} One of the things that any agency/company/government wishing to mountain-build must do is to choose “regulators” that won’t interfere with its plans. In the DOE Complex, one such group is the INL’s DOE-funded, Site Specific Citizens Advisory Board (SSCAB). It’s not really their fault though because DOE can block anyone it chooses from membership on that board and everyone so-considered must promise to go along with whatever its leadership desires – all of its advice/conclusions must be “unanimous”. Furthermore, DOE doesn’t even have to act upon its advice.
entrepreneurial activity and therefore should be, but often isn’t, trammelled by rules/regulations that serve the common good. For instance, in the 1970s, continued nuclear power development was still seen by most of the first world’s decision makers as essential to serving the energy needs of an increasingly affluent and quickly growing population. However, uranium supplies were suddenly threatened by the imposition of a protectionist U.S. embargo that compelled its power utilities to use only U.S. sourced uranium. That embargo was imposed in spite of the fact that some of those foreign mines had been developed with U.S. government encouragement. It depressed prices from other sources, threatening to force closure of some of Canadian, Australian, and South African uranium mines. In response, the Canadian government led in the creation of a world uranium cartel supposedly so secret that any Canadian who talked about it could be jailed. Its existence was first brought to public attention when confidential documents were stolen from the files of an Australian company in 1976. It’s another sad story too long to detail here (see Gray 1982) but the point I’m getting at is that that OPEC-like cartel quickly succeeded in pushing the price of uranium up by ~ 700% thereby destroying any confidence that the world’s nuclear power utility owners may have had about the future price of their fuel.

Cornering the market on anything from filling teeth to supplying government-mandated “EpiPens” remains as much of a goal of free enterprisers now as it did then. Implementing a “Clean New Deal” represents a potentially much more important/lucrative business opportunity than is the making of EpiPens (or insulin) and thereby provides even more temptation for selfish behavior. This is another reason why a nuclear renaissance should not require a fuel that could be so-controlled again. Natural uranium and thorium are so abundant that if they could be efficiently burned, no one could corner the fuel market.
Finally civilian nuclear power has been subjected to “technological lock-in” for many decades because its first movers succeeded in establishing a profitable business model that didn’t emphasize efficiency or long term sustainability. It worked for quite a long time but its weaknesses eventually rendered nuclear power much less attractive than it should/could be (see Cowan 1990)

8.2 Tribalism:

Tribalism is “paying attention only to those who think as we do and considering anyone else an “outsider” to be ignored,” aka, ‘groupthink’. Examples include: Democrats vs Republicans; management vs workers; rich vs poor; businessmen vs technical nerds; experts vs the “dumb public”; regulators vs businesspersons; INEL’s vs Hanford’s radwaste experts; the Chem Plant’s “true believers” vs its agnostics; Shia vs Sunni; “environmentalists” vs pro nukes; and finally, almost everyone vs a whistleblower. Why does Africa now have 54 different countries? For that matter, why does the USA have 50 no-longer-very-united states?

The western world’s currently rising tide of tribalistic nationalism brings out the worst in us. Humans like chimpanzees are apparently hardwired to categorize others of our own species as “thems” not “us” triggering the hate, fear, disgust, violence, selfishness, etc. that we’re seeing more

166 By the time that I came on board, most of the Chem Plant’s choicer job slots were occupied by Latter Day Saints (LDS). The reasons for this include: 1) LDS children are brought up to believe that the System’s leaders are always right; 2) the church encourages them to help each other out; and, 3) as far as “business ethics” is concerned, anything goes as long as it’s apt to benefit the “family”. When fascism comes to America, it will be wrapped in the flag and carrying a cross”, Sinclair Lewis.
of now than since the end of WWII (Sapolsky 2019). Solving the world’s biggest technical problem (replacing fossil fuels) will require its people to cooperate, not retreat further behind their own borders under the goading of populistic leaders taking advantage of our all-too-human nature. It can be overcome by the right sort of leadership but rarely is.

Diversity of thinking is vital if a group facing a complex problem wants to arrive at a competent solution.

Disciplinary (tribal) boundaries often hinder scientific progress because each of its discipline’s adherents resent attempts by Jack-of-several-trade outsiders to either poach upon their bailiwick or evaluate their efforts. This often manifests itself as difficulty in getting anything that might be considered “controversial” accepted/published in another specialty’s peer-reviewed journals. Another very real fact is that scientific journalism’s anonymous reviewers are simultaneously free to turn down such papers (or research proposals), and then subsequently “discover” the concept and study/describe it themselves.

167 I’ll probably go to my grave with <100 peer-reviewed publications because I’m no longer convinced that publishing in professional technical journals is worth doing for people in my position (both retired & unconnected). You must write in a stilted fashion carefully avoiding anything that’s too controversial, there are now too many journals, and, finally, the "best" ones typically charge their contributors several thousand dollars/paper and then turn around and charge anyone who wants to actually read what you’ve written, $35-$50. Since I now have to pay my own bills, that business model means that I rarely read anything in toto that isn’t published “open access”. Thanks to the internet (GOOGLE, Engineering toolbox, WIKIPEDIA, RESEARCHGATE, Science Daily News, etc. plus some still “connected” friends) and the fact that some papers are indeed published “open access”, it's now possible for people like me to pursue science as a hobby. It’s been fun.

168 That happened to me while I was an “assistant” tenure-track professor of chemistry at Marquette University. During my second year there, I’d written an NSF proposal having to do with atomic fluorescence spectrometry, a field in which there was only one active research group
Most people are reluctant to eschew the beliefs of their peer group, regardless of how unsubstantiated they may be. For example, during the early 1980’s Argonne got a head start on what came to be considered its *signature* Generation IV project at DOE’s Idaho site. Within about five years they’d become ready to demonstrate how safe their liquid metal cooled fast breeder reactor would be. Scientists and engineers from around the world gathered to watch what happened when Argonne’s engineers deliberately caused a total loss of coolant (liquid sodium) flow to EBR II. Exactly as predicted, its core temperature briefly increased and then rapidly dropped as it safely shut itself down without further intervention.

Although the IFR project was a technical success in some respects, it couldn’t buck the USA’s anti-nukes & thereby address the problem serving as its raison d’etre. The majority of environmentalists (one tribe) reflexively oppose nuclear power along with many of the Democratic Party’s “liberals: (another tribe) - so the Clinton administration shut it down because “we don’t need it” even though its leader (and certainly his vice president) were aware of the issues posed by anthropogenic climate change. The same thing happened at the beginning of the Obama administration – funding for the GEN IV nuclear reactor R&D (GNEP) program instigated by President G.W. Bush was axed\(^{169}\) and

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\(^{169}\) Another reason for that cut-off was that the special interest-driven (banking) investment rule changes (regulation removal) introduced by the previous US administration had led much of the
the US taxpayers’ thirty-year/$15 billion dollar investment in DOE’s YM spent fuel storage site\textsuperscript{170} was also wasted.

This was not surprising for several reasons, one of which was that two of the people responsible for authoring MIT’s seminal. “The Future of Nuclear Power” (MIT 2003), Professors John Holdren and Ernie Moniz, subsequently served as President Obama’s technical/scientific advisors a half decade later. Three of that report’s conclusions were as follows:

\textit{“ Placing increased emphasis on the once-through fuel cycle as best meeting the criteria of low costs and proliferation resistance;}

\textit{Urging DOE to establish a Nuclear System Modeling project that would collect the engineering data and perform the analysis necessary to evaluate alternative reactor concepts and fuel cycles using the criteria of cost, safety, waste, and proliferation resistance. Expensive development projects should be delayed pending the outcome of this multi-year effort.}

\textit{Giving countries that forego proliferation-risky enrichment and reprocessing activities a preferred position to receive nuclear fuel and waste management services from nations that operate the entire fuel cycle.”}

world into a deep economic recession which, of course, affected governmental spending everywhere.

\textsuperscript{170} It’s likely that if everyone had simply agreed to call YM a “monitored retrievable radioactive waste storage facility” rather than a “repository”, it would be serving that purpose and thereby providing several hundred good-paying jobs for members of Nevada’s “middle class”.

Basically, what this strongly suggests is that President Obama (a lawyer by education) was told by two of this country’s top ranked technical experts that developing a sustainable nuclear renaissance wasn’t really necessary. Since nuclear power represented just one part of a temporary “bridge” to the future\(^\text{171}\), “all of the above” (?) plus a few small modular conventional-type reactors seemed to represent the best way to address the USA’s future energy issues.

An update of MIT’s report almost a decade later (MIT 2011) didn’t change its recommendations or even bother to mention salt-type reactors.

“Secret ingredient of nuclear success: Independent regulation” By Dale Klein, Peter Lyons and Richard Meserve is (07/23/19 05:00 PM EDT) is another self-serving opinion piece written by another three of the people collectively responsible for the USA's decision to just keep kicking the same old ball down the same old road (to nowhere). They share responsibility for President Obama’s espousal of "all of the above" rather than the development of a "renewable" nuclear fuel cycle.\(^\text{172}\) The inability of the NRC “experts” being lauded in this case to evaluate anything other than conventional reactor concepts remains one of the biggest hurdles facing anyone who wants to devise something better.

In a finite world, no person or country can afford to do “all of the above”– choices must be made and a project’s success/failure will

\(^{171}\) They apparently assumed that the other and much bigger part of that temporary bridge would be the tight gas & oil fracked out of the USA’s shale and sandstone formations.

\(^{172}\) It’s probably not a coincidence that the nuclear industry’s business-model reactors /fuel cycle are perfectly suited to remain a small part of “all of the above” for a century or so.
depend upon whether or not they were the correct ones. Fossil fuels regardless of how they are obtained do not represent a sustainable energy source, biofuels cannot replace fossil fuels, wind/solar power is and will remain ineluctably unreliable, and batteries are and will remain too expensive for anything but niche applications. Mr. Obama’s DOE didn’t make much progress because its leadership refused to think quantitatively and make politically tough choices. Consequently, he/they got it backwards: fracked gas/oil and and today’s renewable energy sources should be considered temporary bridges to Hubbert and Weinberg’s nuclear-powered future.

8.3 Gullibility:

“Willingness to embrace logical fallacies”; e.g., “appeal to authority”, “appeal to fear” (it’s no secret that in US industries, poor team players experience “solitary, poor, nasty, brutish, and short” careers\(^\text{173}\)); “wishful thinking” (see my discussions of the consequences of USA’s reprocessing waste management decisions); “sunk cost” (decisions tainted by an accumulation of emotional investment – the more already spent upon something, the harder it becomes to abandon); and finally, “appeal to ignorance”; e.g., “extremely low level radiation dose rates

\(^{173}\) One of Admiral Rickover’s especially sapient quotes is, “"If you're going to sin, sin against God, not the bureaucracy; God will forgive you but the bureaucracy won’t." Fear of job/career loss is a pretty effective motivator for DOE’s “technical” people, especially those who still have mortgages & dependents to support. So too is the fact that its trouble makers are “disfellowshipped” until their managers can come up with a plausible-seeming excuse for reorganizing them out of their jobs (e.g., their expertise won’t be included in the next project’s personnel “skills mix” requirements). Questioning anything makes you a suspicious character – certainly unpatriotic & almost as evil as a whistleblower or “disgruntled” employee.
must be evil because you can’t prove that they aren’t” (it is statistically impossible to prove such things).

The USA’s “conservative” dominated federal government’s manifest incompetence has recently inspired a number of liberal young & not so young politicians to espouse a "Green New Deal" calling for a transition away from a world primarily powered with fossil fuels to one powered by Dr. Jacobson et al.’s 100% wind, water, & solar (WWS) scheme.

In most Western countries it’s the “progressives” and socialists who claim to care more deeply about the environment that seek to shut down nuclear plants, not the politically “conservative” people that usually choose to disbelieve in climate change. Consequently, progress on addressing climate change within the US has come to a standstill because most of its liberals cannot fathom that any rational human can doubt an overwhelming scientific consensus on the issue & neither side is willing (or being forced) to compromise. The political left’s energy-source leanings are illogical because two of nuclear energy’s greatest successes are Sweden and France, nations regarded by many liberal-leaning people as the best kind of societies. Through a combination of sensible policies and free-market incentives, starting circa ~1970 Sweden cut its per capita GHG emissions by a factor of three while doubling its per capita income and providing even more of its notoriously “pro-people” social benefits with nuclear power. A new Swedish book’s subtitle contends that it, much as France had almost done before, has already “solved climate change” by expanding its electrical supply with nuclear power (Goldstein & Qvist 2019). Sweden’s primary concern at that time wasn’t global warming but reliability: its leadership deemed further hydropower development too environmentally impactful and that decade’s OPEC-driven oil crises had rendered fossil fuels too unpredictable. Consequently, between then and
1990, Sweden built a dozen nuclear power plants on four different sites, eight of which continue to operate today. They currently supply ~40 percent of Sweden’s electricity which is as much as do the hydropower plants that Mother Nature had liberally endowed both it and Norway with the potential to employ. Consequently, electricity in both of those countries is still cheap, clean and reliable. The authors of that book contend that, “Sweden became the most successful country in history at expanding low-carbon electricity generation and leading the way in addressing climate change”. They also say that, “without growth in nuclear power, replacing fossil fuels with renewables simply decarbonizes the existing supply. It doesn’t deal with the increased demand...”.

In the real world, it’s been nuclear energy, not solar and wind that has decarbonized energy supplies while increasing wages and societal wealth.

And it is only nuclear that has powered high-speed trains everywhere from France to Japan to China, thereby decarbonizing transportation – the source of about one-third of anthropogenic GHG emissions. Consequently, it seems reasonable to expect that a “Green New Deal” incorporating nuclear power is apt to be more successful and certainly less environmentally impactful than one that doesn’t.

I suspect that one of nuclear renaissance’s most “evil” characteristics as far as many of the green movement’s true believers is concerned is that it would not require their fellow citizens to embrace their faith in the notion that that non-nuclear renewable energy system wouldn’t seriously upset their descendant’s lifestyles: a properly implemented nuclear renaissance would let everyone go on living in pretty much the same way that they’ve/we’ve gotten used to without having to worry about
whether the power will go down (“load shedding”) in the middle of whatever they might try to do.\(^{174}\)

### 8.4 Laziness

[Unwillingness to work] A “good” example of this would be how eager people seem to be to assign a label to whomever brings up a perplexing question so that that they can adopt an already-established paradigm complete with talking points and therefore quit worrying their pretty little heads about it. For instance, whistle blowers are invariably characterized as “disgruntled employees” meaning that whatever might be saying can be comfortably ignored. In the DOE complex whatever a single whistleblower might say is easily dismissed because it’s “just a difference in professional opinion” from that of the majority of his equally-credentialed colleagues working on the same problem. For both decision makers and their “outside” advisors laziness means not taking the time to learn the fundamentals of whatever it is that they are supposed to be over seeing. Ignorance – especially if it’s deliberate –

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\(^{174}\) Coal power even in coal-rich countries isn’t necessarily reliable (Enerdata 2019). South Africa’s Eskom – the African continent’s biggest power utility by far - has just decided to take 4,000 MW off its power grid. On 14 March 2019, the first 800 MW unit of its Kusile power plant tripped, exacerbating a shortfall of generating capacity and prompting it to announce a Stage 2 (2 GW) load shedding, that changed into a Stage 3 (3 GW) and finally into a Stage 4 (4 GW) load shedding, after the loss of additional including 900 MW imported from Mozambique due to storm damage to an interconnection to its Cahora Bassa hydropower plant). Its existing plants suffer many breakdowns and the construction capacity, of two more big ones (4.8 GW each), is running years behind schedule and billions of dollars over budget. In mid-March 2019, ~12 of Eskom’s 45 GWe total capacity was unavailable due to unplanned outages and its back-up diesel supplies were also under pressure. Eskom is now US$29bn in debt and South Africa’s government has announced plans to restructure it and support some of its short-term debt issues.
should never represent an excuse for any failed technical project’s leadership but often does\textsuperscript{175}.

Because DOE’s “technical” decision making is primarily driven by immediate political considerations and artificial schedules, its top level managers rarely bother to acquire much relevant “subject matter expertise”. The people who provide them with such services – mostly senior contractor employees – are rewarded for saying/writing/supporting whatever “the customer” happens to want at any given time; e.g., an excuse for espousing “separations” instead of »direct vitrification« of INEL’s radwastes - and eventually downsized if they persist in not becoming good team players\textsuperscript{176}.

The funniest example of this “symptom” that I can remember was back when we lab rats had just been informed that INL’s (then INEL’s)“new mission” would be to become the “lead lab” in radioactive waste management and DOE’s brand new Assistant Secretary of Energy (Management and Administration) had decided to go out and meet the stakeholders. When asked by a newspaper reporter to define “High Level Waste” everyone learned that...

\textsuperscript{175} The excuse of last resort is that a repeatedly failed project is/was “first of a kind”. In most such cases that’s true because no other institution would have initially decided to try to address that problem that way. DOE’s managers do so because they can always blame/change contractors and about the worst possible punishment that a >50 year old civil servant can suffer is a well-funded early retirement (a government contractor’s personnel are not similarly protected).

\textsuperscript{176} The most common way of downsizing troublemakers was to not include her/her expertise in the Site’s next project’s “personnel skills mix requirements”.
“Well it is a radius that is applied to it on a high level in a way that you are going to treat that way, and the way that you are then going to process it. So at the end of that, on a high level, let’s say you might have to – after processing that, you may-before you put it into the permanent storage, that may be something that you have to transport to let’s say - to where we were putting storage in New Mexico. Some other kind of waste you could be able to put in the cement and store it right there on the site. High level, we would handle that with care. We handle all of it with care.”

That really cleared things up for us newbies.

8.5 Deviousness

(Deliberately misleading others to serve your own purposes).

In DOE’s technical reports this is usually evinced by deliberately not addressing what should be the subject’s “obvious” issues/questions while emphasizing the importance of whatever its author is doing or proposing. This usually “works” because the real customers for such information (top level managers, funding sources, politicians, and/or important citizen stakeholders) are often technically clueless and simply seeking reassurance that everything is going along just fine\textsuperscript{177}. The reason that DOE's nuclear arm has become dysfunctional and its documentation/advice unreliable\textsuperscript{178} is that its people, top-to-bottom, 

\textsuperscript{177} The most important part of any DOE report is a carefully “filtered” executive summary.

\textsuperscript{178} As Sinclair Lewis said almost a century ago, “every compulsion is put upon writers to become safe, polite, obedient, and sterile”.

have behaved and written the way they felt their bosses expected/wanted them to (see APPENDIX XIII). That’s also why its documents and contracts undergo so many “revisions”\textsuperscript{179}.

In the broader “nuclear world”, it’s generally verboten to say anything negative about what’s being done to devise something that fits current paradigms. Consequently, since top decision makers now consider nuclear power be only a relatively minor part of “all of the above”, any “new” reactor concept suitable for some sort of special niche somewhere is enthusiastically welcomed. For instance, a popular pro nuke blogsite hosted by someone who is technically competent, recently posted a breathless description of the SLIMM concept - a “disposable”\textsuperscript{180} 10 - 100 MW(thermal – about half that much electrical) sodium cooled reactor that would be eminently safe & simple because it wouldn’t need pumps to move its coolant (Mohamed 2015). The downsides of that idea are as follows:

- it’s terribly inefficient both resource and cost wise – “small” in terms of energy output but large in terms of steel, labor & fuel inputs & therefore cost
- although its design is based upon the results of Argonne’s liquid metal-cooled breeder reactor research, it’s terribly inefficient U fuel-wise

\textsuperscript{179} For instance, after INEL’s new naval fuel dissolution facility proved to be far less productive than “promised”, previously published reports were revised to eliminate specific throughput estimates & the original versions gathered up & destroyed. The same thing happened with the reports having to do with its decision to “steam reform” its remaining liquid reprocessing waste.

\textsuperscript{180} “disposable” because when its fuel is burned up, it’s removed and hauled off somewhere.
The heat energy generated before the "big" version of the thing has to be removed/replaced (5.8 full power years (fpy) at 100 MWt) corresponds to 1.8E+16 joules which would require 223 kg worth of fission. If that's 20% of the total HM in the core (a pretty high EBR II burnup) that's 1115 kg total U. Since its fuel is to be 17.75% enriched $^{235}\text{U}$ that's 198 kg of “startup” fissile added to get that 223 kg's worth of heat. That figure is worse than that of a typical PWR.

Consequently that particular concept doesn't represent a nuclear solution to the future's energy issues any more than do NUSCALEs or TOSHIBA 4S's. It's just another special little niche-filler for powering something like a cost-is-no-object military base (Area 5?).

Since any nuclear fuel cycle capable of "saving the world" is going to have to be able to generate at least 20 TWe - that's at least 40 TWt (~400,000 SLIMMs), it’s also going to have to be breeder-based (CR=>1) because it'd be fuel limited otherwise. Consequently, as far as our descendants’ real problem is concerned, little toy concepts like SLIMM represent expensive distractions, not solutions. Technically educated pro nuke bloggers should point that out when reporting upon the latest/greatest goings on in their bailiwick.

I’ve told everyone who’s invited me to become a member of their MSR nuclear startup team that being "sneaky" about what you are proposing to do is no longer apt to win hearts and minds (certainly not mine) – too many people have been snookered too many times by the nuclear industry's experts. That cultural foible is what finally made me decide
not to align myself with any of them\textsuperscript{181} - protecting "IP" is just another excuse for devious behavior and likely cause of \textit{eventual} failure.

APPENDICES XIII & XIV detail specific examples of institutional deviousness.

\section*{8.6 Bullheadedness:}
Once we humans decide to look at things in a certain way (establish a “business model”), it’s extremely difficult to change our paradigms/minds even when it becomes obvious to “outsiders” that it’s not working. Here are some examples….

\subsection*{8.6.1 “Working class” politics}
During the run-up to the 2016 Presidential election, the USA’s less conservative political party appeared to be ignoring the USA’s working class because it didn’t tell them what they wanted to hear. Its candidates lost that election because many (not all) “normal” people prefer a comforting lie to an uncomfortable truth & vote accordingly.

An example would be the folks in the USA’s “coal country”. Like many working people, coal miners are indeed suffering financial worries and the left didn’t ignore them. Hillary Clinton proposed a massive $30 billion program that would shore up coal pension funds in failing coal companies, offer free job training to prepare their workers to move into other fields, and support coal plant modernization to make them cleaner and more efficient.

\textsuperscript{181} I did some work for three of them but backed out when it became apparent that their goals were inconsistent with those identified in this book.
In other words, she basically said, “Coal has almost run its course “, “you can’t just keep doing what you’re doing”, and, “I’ll help you do something else.”

Many working people don’t want to hear things like that (too much change). They’d rather hear about how great coal’s future is.

Overall, most of the USA’s working class’s current “issues” are a consequence of its supply and demand-based economic system. As the supply of cheap immigrant labor went up and women entered the workforce (effectively doubling the labor pool) while the demand for low tech-type labor was going down due to outsourcing and automation, what « unconnected » individual employees got paid for their labor fell well below what they had come to expect.

While this was happening, incessant advertising, multi income families, easy credit, “privatized” health care, and population growth increased demand for consumer goods, housing, land, and high-end services driving up their prices.

There was also an “everyone must go to college” push that that drove up its cost due to increased demand plus more easy credit (student loans) while driving down the value of a college degree due to increased supply.

Those trends depressed real wages for almost everyone.

(Many “important” people don’t want to hear things like that because they’re in the minority that benefited from those changes.)

Consequently, when Mr. Trump told them that he could quickly fix everything by undoing everything that Mr. Obama had tried to accomplish, they decided to don their brand new red MAGA hats & vote with their feelings. Some of them (especially the USA’s soybean &
southern-border produce & fruit farmers) are beginning to realize that that might not have been a wise thing to do. The others, probably the majority, are apt to double down at the next election unless the “Trump recession” (the big one) sets in before then.

8.6.2 Anti-nuclear “environmentalists”
Reflexively antinuclear environmentalists are especially bullheaded\textsuperscript{182}. The real world limitations of wind, solar, and even hydropower\textsuperscript{183} that most of them refuse to recognize means that every time they vote/rail against nuclear power, they inevitably vote for the fossil fuel industry, especially oil and gas fracking. It’s likely that those fossil fuels’ suppliers are delighted since they know that for the foreseeable future, the only thing that can replace nuclear power plants shut down by such activism are new coal (in Germany) and natural gas-fired plants. Since “No Nukes” became a signature cause of the Green movement in the late 1970’s, sympathy to nuclear power became a sign of disloyalty if not treason to many environmentalists.

Today’s rabid antinukes are much like the people decades ago who were “enraged” about the environmental effects of the “green

\textsuperscript{182}Paul Ehrlich, one of the recent past’s most influential misery-mongers famously opined that giving cheap, abundant energy to humanity would be like “giving an idiot child a machine gun”. Today’s idiot children, some of whom are over 70 years old and hold high elected office, are threatening other countries with “smart” fossil-fueled drones capable of delivering the latest generation of mini/micro nuclear weapons.

\textsuperscript{183}One of the assumptions underlying the 100% WWS (Wind Water & Solar) scheme is that dams (that proposal’s “batteries”) could temporarily provide over an order of magnitude more electricity than they actually could. One problem with that assertion is that existing “good dam sites” aren’t big enough to accommodate an order of magnitude more power houses/turbines. Another is that such massive and sudden water releases would flood anything down steam of them.
revolution” that subsequently made it possible to feed today’s ~7.5 billion people. Professor Borlaug dismissed their concerns with, "some of the environmental lobbyists of the Western nations are the salt of the earth, but many of them are elitists. They’ve never experienced the physical sensation of hunger. They do their lobbying from comfortable office suites in Washington or Brussels...If they lived just one month amid the misery of the developing world, as I have for fifty years, they'd be crying out for tractors and fertilizer and irrigation canals and be outraged that fashionable elitists back home were trying to deny them these things.”

James Ephraim Lovelock, CH CBE FRS is a very senior (born 26 July 1919 independent scientist, environmentalist, and futurist best known for proposing the Gaia hypothesis, which postulates that living organisms interact with their inorganic surroundings to form a synergistic, self-regulating, system that serves to maintain and perpetuate the conditions necessary for life. His best known book, Gaia’s Revenge, points out how mankind is defeating that system. He is also often considered to be a turncoat to the environmental movement

“A television interviewer once asked me, "But what about nuclear waste? Will it not poison the whole biosphere and persist for millions of years?" I knew this to be a nightmare fantasy wholly without substance in the real world... One of the striking things about places heavily contaminated by radioactive nuclides is the richness of their wildlife. This is true of the land around Chernobyl, the bomb test sites of the Pacific, and areas near the United States' Savannah River nuclear weapons plant of the Second World War. Wild plants and animals do not perceive radiation as dangerous, and any slight reduction it may cause in their lifespans is far less a hazard than is the presence of people and their pets... I find it sad, but all too human, that there are vast
bureaucracies concerned about nuclear waste, huge organizations devoted to decommissioning power stations, but nothing comparable to deal with that truly malign waste, carbon dioxide.” (Lovelock 2006)

As did I, James Lovelock started out as an analytical researcher endeavoring to push the detection limits for toxic substances ever lower. His signature invention, the electron capture detector, permitted the detection of refrigerant-type chlorocarbons in the stratosphere – a feat that resulted in the policy changes constituting the single greatest success of the modern environmental movement - “closing the ozone hole”. However, it also permitted the detection of chlorinated pesticides in foods, water, etc. at levels far lower than could possibly hurt anyone or anything. The human nature-driven consequences of those policy changes plus his opinions about nuclear power caused him to break ranks with most of the people spearheading the world’s “environmental” movements.

Dr. Lovelock’s point was that the real reason that the area around Chernobyl is still uninhabited (by people) is due to the way that we humans currently respond to any sort of nuclear accident. It’s a lot like we used to act back in the seventeenth century when we were told that someone was a witch - like frightened chickens

8.6.3 Hyper secrecy

Even scientists and engineers often equate arbitrary and often poor human-made decisions with Nature’s laws. Unfortunately, nuclear power was an afterthought of a post WWII rush to develop super bombs

184 I was a fairly well-known graphite furnace atomic spectroscopist during the 1970s-80s..
and submarines that could stay down indefinitely, move quickly, and break things. Of course, as such, everything about it/them became a secret that only special experts and certain authorities could access. Secrecy within the DOE complex has been gradually getting worse ever since the end of the Clinton administration, but Mr. Trump’s DOE performed the coup de grâce by completely pulling its public-facing employee directory (“DOE Phonebook”) behind an impenetrable firewall, thereby making it far more difficult for journalists and members of the public to locate the email addresses and/or phone numbers of its employees both civil service and contractor. Consequently, it has become almost impossible for an outsider to discover who’s actually responsible for doing anything at DOE’s laboratories.185.

Rendering federal scientists and policy makers harder to contact isn’t a trivial matter. Firewalls shield taxpayer-funded government employees from the outside world, meaning that they don’t experience much public feedback and can therefore continue to do whatever they please. This has been getting worse since the end of the Clinton administration, which is why everything about nuclear power R&D has become even more tarred with the same brush as has nuclear weapons development. A

185 Even information obtained via a “Freedom of Information Act” (FOIA) request usually serves to protect our government’s decision makers. An example of this came to light when a lawyer representing two of Idaho’s ex governors (Batt and Andrus) made a freedom of information request to DOE about specific questions regarding obviously already made decisions regarding shipments of spent fuel rods to INL prior to any environmental analysis or public input: “The response is a joke,” Lucas said. “They have redacted almost all their supposed answers and are claiming national security concerns on almost every question. Literally, DOE has not produced a single document that was not already public,” violating the Freedom of Information Act.” (Advocates 2015).
nuclear power plant can’t explode like a nuclear bomb\textsuperscript{186}, but many people think that it could and, quite justifiably in my opinion, no longer trust that industry’s spokespersons.

The USA’s determination to classify anything “new” having to do with nuclear reactor development is one of the reasons why it neither leads the world in that field nor is apt to regain leadership. This compulsion has recently been rendered more destructive by its government’s decision to pit the USA’s entrepreneurs against each other to engender a renaissance that it should assume responsibility for developing\textsuperscript{187}. Consequently, those “best and brightest” US citizens likely most capable of implementing change are forced to not cooperate with each other in order to protect their ‘intellectual property” That is, of course, perfectly OK with the secrecy-obsessed governmental managers responsible for “helping” those go-getters with research grants and/or vouchers that can

\textsuperscript{186} The two reactor explosions” that I’m aware of – that of the US Army’s SL-1(Stationary Low-Power (3 MWt) Reactor Number One) and the USSR’s Chernobyl disaster - were steam, not nuclear, explosions that immediately shut down both of them. For example, the deliberately caused (suicidal) “transient” that shut down SL-1 generated about 20 GW for about four milliseconds (SL-1 2019). That’s 8E+7 joules which means that about one milligram of its fuel was consumed by it – a small nuclear bomb’s explosion consumes 5- 6 orders of magnitude more fissile.

\textsuperscript{187} The US federal government is encouraging people who grew up during a time when exploiting "intellectual property" had become the best way to become rich and famous, to decide what should be done or investigated. There’s a lot more to implementing a sustainable nuclear renaissance than just creating or cornering IP. Pitting entrepreneurs and/or contractors against each other to do the government's job simply sets up another situation in which the biggest liar is apt to "win". The development of a reactor/fuel cycle able to affect Weinberg's "Age of Substitutability" is too big, too important, and too potentially dangerous to turn over to people/institutions primarily motivated by personal gain/profits or immediate political drivers. Everything we know about achieving it should immediately become "open access" and permanently kept that way.
be spent only at national laboratories (thereby giving their own employees another number to charge their work time to). This paradigm assumes that people in other countries are incapable of either doing such research for themselves or even reading reports published by the citizens of countries that haven’t chosen to similarly hamstring themselves.

It also happens to be absolutely contrary to the guidance that Alvin Weinberg gave his young colleagues at ORNL fifty two years ago:

“Good people from diverse fields working together can make scientific discoveries that are denied to solitary geniuses working in isolation. Such coherence in applied research projects is even more important.”

8.6.4 My own bullheadedness

A final example would be my own refusal to pretend to just go along with whatever the System was apparently determined to do and then try to change things as an “insider” rather than an outsider (see APPENDICES VII & VIII). That may have even worked, who knows? For instance, I’ve never become a member of the American Nuclear Society despite having several papers relating to some of the technical aspects of how a fission-based nuclear renaissance might best be implemented published in its peer-reviewed journals. The main reason for this is that the ANS is dominated by people/institutions that are in one way or another, responsible for that discipline’s technical stagnation. For example, the person who headed-up US DOE's nuclear engineering R&D program during the latter half of the Obama administration (it’s “NE 1”) was chosen to give a plenary talk at the 2017 National ANS meeting. As far as I was able to tell throughout his tenure, both he and his counterpart on DOE’s “waste” side (its “EM 1”), just kept kicking their respective cans on down the same road (to nowhere) without apparent interest in learning why they shouldn’t do so. People who receive such honors from organizations like the ANS tend to be
exceptionally good “team players”, not visionary technical experts. Unfortunately, the top-down driven institutions that employ them (DOE and its contractors and other business partners) impose blinders upon their employees which keep them from doing anything inconsistent with their employer’s immediate interests which, in turn, are driven by the policies/attitudes of the USA’s political leadership.

8.7 Bullheadedness’ Consequences

8.7.1 INEL’s calciner’s off gas “opacity issue”
One of DOE’s Idaho laboratory site’s most distinguishing features was that when its nuclear fuel reprocessing plant’s waste calciner was being productive, a huge, somewhat toxic\textsuperscript{188}, golden-brown plume of NO\textsubscript{x} would stretch out downwind of its ~300 ft. high “smoke” stack. That plume would occasionally wander over the ~25 miles-away “Craters of the Moon” national monument & thereby engender an “opacity issue”. INL’s calciner operated at about 500ºC and was heated by squirting kerosene along with the liquid waste into the bottom of an excess-air fluidized bed reactor\textsuperscript{189}. All of the liquid wastes so-calcined consisted of mixtures of water, nitrate salts, nitric acid, and, often, some fluoride salts too. With “high fluoride” wastes, a great deal of calcium and aluminum nitrate salts (more nitrate) were added to “complex” it (reduce corrosivity) while it was still liquid and suppress HF volatilization.

\textsuperscript{188} Both its odor and effects are similar to those of chlorine gas.

\textsuperscript{189} In a fluidized bed reactor, a fluid (usually a gas) is passed up through a “bed” of solid granular material (e.g., already-formed calcine) at a velocity sufficiently high to suspend those particles causing the system to behave as if it contained a well-mixed low viscosity fluid. They are used to carry out a variety of multiphase chemical reactions.
during its subsequent calcination. Under those conditions the majority of nitrate salts\textsuperscript{190} and all of the nitric acid decompose to form a mix of NO and NO\textsubscript{2} which along with excess air, elemental nitrogen, water vapor, and CO\textsubscript{2} was filtered and then sent up the stack. Because a lot of that waste (anything created by reprocessing zirconium clad fuel) did indeed contain fluoride, a great deal of calcium nitrate was added most of which was imported from Sweden because it was cheaper than that from US sources. At the same time that this was going on, the site’s reprocessing plant’s facility’s fuel dissolution experts were importing lots of nitric acid.

In the late 1980’s I pointed out to my management that the NO\textsubscript{x} in the calciner’s off gas would be easy to recover/purify\textsuperscript{191} and that doing so would be advantageous to them/us in several ways. One was that because NO\textsubscript{x} is both highly visible (impossible to hide) and somewhat toxic, it was generating “stakeholder” complaints (by that time, it was illegal to emit nearly that much NO\textsubscript{x} anywhere else in the USA). The other was that scrubbing/condensing it out of the calciner’s off gas to make the nitric acid and calcium nitrate that we’d otherwise have to import would certainly be politically correct and might even save us some money. However, management didn’t want to change procedures or complicate their jobs so that suggestion was ignored – the Federal

\textsuperscript{190} Alkali metal (sodium and potassium) nitrate salts are the exception – at 500°C they melt to form a glue-like liquid that “agglomerates” (aka “rocks up”) the sand-like particles comprising the calciner’s fluidized bed which eventually shuts it down.

\textsuperscript{191} Nitric acid is normally made by scrubbing an oxygen plus NO\textsubscript{x} gas mix with water which means that the only “new” thing required would have been a more-or-less off-the-shelf gas scrubber. The INL’s reprocessing facility already had a large distillation system which could have purified/concentrated such acid.
government’s nuclear facilities could flout its own laws then and apparently still can\textsuperscript{192}. Similarly, a few years later when it became apparent that INL (then INEEL) should immediately calcine its million gallon inventory of still-liquid “sodium bearing” reprocessing waste, its management chose to shut that calciner down rather than change their paradigm\textsuperscript{193} which, eventually led to the billion-dollar SBW “steam reforming” boondoggle that I’ve already described.

### 8.7.2 Argonne Idaho’s IFR waste management scheme.
Nearly four decades ago the United States decided to focus its sustainable reactor development efforts exclusively upon Argonne National Laboratory’s plutonium-breeding, liquid metal–cooled, fast reactor. Consequently, that concept currently represents the only genuinely sustainable nuclear fuel cycle that could be implemented “quickly” (and then only if we were to suddenly become willing to buy Russian-built reactors). Unfortunately, as developed, it possesses a number of drawbacks that have rendered sustainable nuclear power a tough sell to both electrical utility CEOs and outside reviewers.

\textsuperscript{192} Forcing people to work without pay is something that only our federal government’s topmost businesspersons can do.

\textsuperscript{193} INL’s calciner was fed from a 10,000 gallon tank containing a mixture of liquid waste plus whatever else deemed necessary (e.g., calcium nitrate for fluoride containing wastes). Mixing such large volumes of an \textasciitilde{}8 molar nitrate salt/nitric acid mixture with enough sugar to prevent agglomeration could become “dangerous” if, for some reason, that mixture wasn’t quickly calcined (it’s thermodynamically unstable and therefore might “explode”). Of course, that’s certainly not the only or logical way to add that sugar (e.g., add molasses via a “mixing tee” added to the pipe running between that tank and the calciner) but any proposal’s trumped up “safety issues” provided the Site’s management with a fine-sounding excuse to not change anything.
One of those drawbacks is that the fission product containing salt waste generated by Argonne’s “electrorefiner” was to be converted to a Ceramic Waste Form (CWF) rather than glass$^{194}$. CWF is a mixture of a low melting powdered glass “glue” and a synthetic sodalite powder made from the electrorefiner’s “hot” (radiologically contaminated) LiCl/KCl electrolyte plus a zeolite which is hot-sintered together to form a ceramic monolith. The problem with that is that CWF is simultaneously difficult/expensive to make, not very durable (leach resistant), and can contain only a small percentage of the fission product waste that the glass-type waste forms produced by the world’s still-functioning reprocessing facilities can.

In other words, an IFR-based nuclear fuel cycle applying CWF to its reprocessing/recycling waste streams would generate 15 to 19 times more high level waste (HLW) form material/GWe-yr than do today’s once through LWRs coupled to a modern Purex-based reprocessing facility. By volume, that disparity would be even greater because CWF is considerably less dense, ~2 g/cm$^3$, than are glasses, ~2.6-3.0 g/cm$^3$.

Turning around a situation like that requires a critical examination of all assumptions inherent to its paradigm (for CWF) in order to identify/challenge/change those rendering it unnecessarily inefficient.

In that case, the key wrong assumption was that an electrorefiner salt’s waste form must immobilize chloride. That assumption is unnecessary

$^{194}$ Glass making (vitrification) has come out on top of every independent (“outside”) US evaluation of HLW treatment options save one. That exception concluded that concretes made with properly “pretreated” (?) wastes might be equally satisfactory and somewhat cheaper. The reasons for that near-consensus are that glasses are compact, sufficiently water-leach resistant, and the process that makes them (vitrification) is relatively safe, simple, and cheap to perform.
because chloride is neither toxic nor radioactive nor difficult to separate. It is also a crippling assumption because none of the durable natural minerals that waste form material scientists set out to emulate can accommodate more than a few weight percent chlorine. Since sodalite $[\text{Na}_8(\text{AlSiO}_4)_6\text{Cl}_2]$ represents the best of a poor lot in that respect (7.2 wt% Cl), ANL’s materials scientists set out to produce an artificial sodalite and therefore ended up with CWF (Simpson 2001).

My first retirement hobby project was to develop a better way to deal with such waste. That effort involved performing a basement-laboratory demonstration of how it could be treated in basically the same way that the USSR had adopted/implemented for that generated by its Mayak reprocessing facility: i.e., mix the waste salt with aluminum and/or ferric oxide and phosphoric acid and then vitrify it (Day and Kim 2005). That process is simple to do, generates an exceptionally durable (leach resistant) and compact glass waste form material, and also renders the separating/capturing/recycling of chlorine easy/simple. (Recycling is the best way to deal with any sort of industrial waste.) It was tough to get that paper published because its anonymous peer-reviewers were all experts involved with the development of CWF – however, that Journal’s (Nuclear Technology’s) editor finally overruled them and

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195 For example, TERRAPOWER and ELYSIUM’s MCFRs would surely run somewhat better with fuel salts containing more or less pure $^{37}\text{Cl}$ – not natural chlorine. Since making such salt mixtures will not be cheap, their chlorine should be recycled, not “encapsulated” within some sort of waste form.
decided to accept/publish it anyway (Siemer 2012). He even waived his journal’s usual page charges.

Not surprisingly, whenever any of INL’s erstwhile fast reactor development experts (most of them have either retired or gotten academic jobs) have subsequently been called upon to render an opinion (or write a paper) about how such waste is to be treated, they don’t seem to remember that there’s been a reasonable alternative to CWF already described/published. The last such paper I’ve seen (Simpson 2013) recommended direct geological disposal of that water soluble, intensely radioactive waste salt rather than trying to turn it into CWF (the only alternative to direct dumping mentioned was an exotic tellurite glass with about the same waste loading limitations as CWF).

8.7.3 DOE’s radwaste classification system

Because we humans invariably take far too long to change our official opinions (rules and laws) when they prove inconsistent with natural law, we routinely waste lots of time and (usually) other peoples’ money when things don’t work out as planned. An especially silly example is the USA’s radwaste classification system. Such waste comes in four flavors: commercial spent nuclear fuel (SNF), high-level nuclear waste (HLW) and transuranic waste (TRU) — both from weapons making — and low-level radioactive waste (LLW) from things like the mining.

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196 In science-type journalism, authors are generally expected to pay publishing houses to have their work reviewed and, if deemed acceptable, eventually published. Both reviewers and (usually) editors are expected to volunteer their services - not paid for their efforts.

197 Such salt would be at least as “hot” as the HLW being vitrified in modern European fuel reprocessing facilities (see APPENDIX IX).
medical, and energy industries. A minor amount of other sorts of radioactive wastes are sprinkled among these categories.

The HLW currently serving to rationalize most of the DOE Complex’s radwaste boondoggling is “high” because it contains some stuff originally within a waste stream (raffinate) coming out of a reprocessing facility’s “first cycle” liquid-liquid extraction system (see APPENDIX I). In other words, the “highness” of a storage tank’s radwaste is determined by the label assigned to the worst fraction of whatever happened to have ended up within it, not by how “hot” (radioactive) or chemically toxic it actually is. The good thing about radioactive-type wastes is that they inevitably become less radioactive as time goes by which is why much of DOE’s 30 to 70+ year old production /test reactor-generated HLW is no longer very radioactive (see APPENDIX 1X). That fact doesn’t matter to most of the folks involved with either performing or overseeing DOE’s waste management projects – “it’s ‘high’ because that’s what they say it is which means we’re gotta (and can) treat it as if were really dangerous”. James Conca has recently written a fine explanation of why the USA’s classification system needs a radical overhaul (Conca 2019).

Let’s end this dismal sub chapter with a joke that I’ve just been told (Dolan 2019) was pretty popular among the INEEL’s in-crowd when they got together at their favorite watering holes after work.

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After the old manager was fired he gave his replacement three envelopes along with this advice: “When you get in trouble, open the first envelope.”

After several weeks the new manager needed to open the first envelope.
The note inside said “Blame your predecessor.” That worked well for a while.

Months later he needed to open the second envelope, which said, “Reorganize your department.” He did, and it worked for several more months.

Finally, his blunders created a desperate situation. He opened the third envelope.

It said, “Prepare three envelopes.”

8.7.4 DOE’s “ethics training” program

Nuclear Complex-wide mandatory ethics training was apparently DOE’s response to the outsider backlash generated by its decision to replace its Idaho Site’s M&O (management and operation) contractor with another (Lockheed) that had recently embarrassed our government’s officials by bribing a foreign government’s officials. The idea behind it seemed to be that if the people that its new contractor was now responsible for managing (us) learned about ethics, their (our) new bosses would no longer behave unethically (?). As far as most of us were concerned it was just another nuisance management fad that would be providing us with an especially valid charge number. Suffering through it made most of my colleagues’ eyes glaze over (probably rendering them a bit dumber & certainly better-rested), but I found those lessons useful (even took notes) because I could now “legally” rationalize my heck-raising about how DOE’s “lead” & otherwise labs were serving the Public. I had never become an insider because I’d always insisted upon looking at technical issues from a point of view defined by the "mission statement" & whatever facts I could gather up about possible options. Consequently, as soon as I started to get involved with the chem plant’s processes, not just its ancillary analytical stuff, I began to become a
“poor team player” & therefore never became an “insider” granted access to its especially important secrets. When that eventually turned me into a whistle blower, the Site’s managers tried to get rid of me circa 1998. However, the “outsider” official arbitrating that disagreement forced them to give me a promotion, a little cash settlement, & a promise to quit hasseling me (they eventually forgot that promise).

Chapter 9. The reasons why the Western world’s erstwhile leader in nuclear energy must “embrace change”

9.1 The USA’s middle class’s issues

Because the USA was virtually unscathed by WWII and had implemented several wise post-war policies, up until about 1970, it possessed a virtual monopoly upon both technological innovation and industrial productivity. However, by the mid-1970s much of that war’s physical devastation and attendant social and economic turmoil elsewhere had finally been overcome. That shifted a significant portion of the world’s industrial production to Asia where cheaper labor, shipping, communication, and overhead costs gradually shifted the USA’s economic system from one based upon production of its own

198 This section begins with a fairly extensive rewrite of “America’s beleaguered middle class”, an article originally written by Richard Larsen & published by the “Idaho State Journal”, February 22, 2014. However, the solution to their/our problems that Mr. Larsen had proposed is different than mine.
goods to one based upon services (which includes selling foreign-made goods to US customers) and consumption.

During that decade millions of foreigners willing to work for wages lower than those that its current citizens expected immigrated to the USA. In addition, millions of recently emancipated women and grown-up baby boomers entered the same labor force. Those demographic changes combined with the globalization of manufacturing and the automation of production everywhere effectively froze real (properly inflation-adjusted) wages for the first time in US history. Because it had become convenient for its top businessmen to do so, the USA also voluntarily gave up its capability to provide some of its people’s needs with locally-sourced mining, manufacturing and agriculture—or even to extend the life of such products through reuse, repair, and repurposing. For example, the rare earth elements (REE) needed to make things like TV screens, computer hard drives, hybrid car motors/batteries, wind tower generators, etc., are no longer produced in the USA because the ore bodies containing them also contain enough of the chemically-similar thorium plus its “daughters” to render them slightly radioactive, which rendered working with them in its regulatory environment prohibitively expensive 199. We no longer even mine/process/enrich the

199 Natural thorium’s half-life (14 billion years) is about three times the age of the Earth meaning that it’s only nominally radioactive. However, because it is generally in secular equilibrium with about ten decay products (“daughters”), any such ore’s total radioactivity is about an order of magnitude greater than that of the thorium itself and is therefore easily detected. The radioactivity of a typical rare earth ore containing 2.5% thorium is ~1000 Bq/g - high enough to render working with it under the USA’s regulatory environment more expensive/troublesome than it’s worth.
majority of the uranium going into our nuclear reactors\textsuperscript{200}. The USA came to rely upon countries more recently empowered/lubricated by “cheap” oil, to meet its people’s wants with their still-cheap labor and natural resources. Furthermore, over the last four decades global per capita consumption of some commodities has grown eight to twelve times faster than has human population. After this century’s inevitable post-peak-oil period, interruptions in the flow of such goods will be profoundly destabilizing to what had once been the USA’s uniquely large & prosperous “middle class”. They had become accustomed to enjoying extra consumption via a combination of both their own and their government’s addictions to deficit spending plus the “off sourcing” enabling low cost expropriation of other nation’s/people’s share of the Earth’s resources\textsuperscript{201}. Demographics, the outsourcing of energy-intensive industries plus automation of most of remaining ones has severely impacted the people who had worked in them, thereby generating poverty, insecurity, plus a great deal of angst and political unrest thereby enhancing their vulnerability to populistic scapegoating\textsuperscript{202}.

\textsuperscript{200} Since the collapse of Soviet Union more than 19,000 Russian warheads have been dismantled and their highly enriched uranium (HEU) diluted to make fuel for U.S. nuclear reactors. During that period more than half the fissile ($^{235}\text{U}$) powering civilian US reactors came from Russia’s “reprocessed” nuclear weapons.

\textsuperscript{201} The latter has become especially convenient to the USA’s political leadership because they could claim that, “it’s them foreigners, not us, that are really polluting the atmosphere”.

\textsuperscript{202} We now routinely blame African Americans, Latino Americans, gays, lesbians, Arabs, China, Persians, women, too-young people, too-old people, Muslims, & “commies” for our problems. The real problem is that the USA’s political system; 1) enables its already-fat hogs to determine who gets the best stuff remaining in its trough, 2) routinely ignores the wishes of the majority of its citizens, and 3) is primarily concerned with getting/retaining control, not doing what’s in the best long term interests of the country.
Where did today’s anti-human (“neo Malthusian”) mindset come from? Senator Elizabeth Warren introduced a new piece of legislation in August of 2018 called the Accountable Capitalism Act which provides a snapshot of how it happened. Here’s the gist of what it says:

For most of our country’s history, American corporations balanced their responsibilities to all of their stakeholders – employees, shareholders, & communities – in corporate decisions. In the early 1980s, America’s biggest companies dedicated less than half of their profits to shareholders and reinvested the rest in the company but then a “new idea took hold: American corporations should focus only upon maximizing returns to their shareholders (i.e., the rich should become richer). Consequently, big American companies currently dedicate ~93% of earnings to shareholders thereby directing trillions of dollars that could have gone to workers and long-term investments in the company itself. Lately, since the easiest way to increase profit margins is via automation, especially when firing people means that you can stop paying their health and insurance costs, that’s what’s been happening. Many of the USA’s middle class people haven’t yet come to grips with the whys of their situation and are responding in the same fashion as did Italy and Germany’s citizens during the 1920/30s as evidenced by the outcome of its last presidential election; i.e., blame “outsiders”, especially foreigners.

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203 In an improperly regulated/motivated capitalistic society doing things like that to low-level employees is as inevitable as entropy.

204 “Remember, remember always, that all of us, and you and I especially, are descended from immigrants” Franklin D. Roosevelt
Consequently the USA’s middle class is shrinking both in terms of population percentage, and qualitatively, in terms of their quality of life. Many of them are being squeezed by declining real incomes and rising expenses as they increasingly shoulder the inflationary costs of both corporate greed and grossly inefficient, special interest-driven, government(s). The USA has moved away from being a “meritocracy”. Wealth inequality has recently increased more than during any other time in its history, while economic mobility has shrunk. Roughly 60 percent of America's wealth is inherited and, like most privileges, is heavily skewed to exclusive groups. In 2012, PBS’s Bill Moyer pointed out that the real median US household income was under what it was at the end of the ’80s and down 9 percent from its peak in 1999, with the biggest part of that decline, 8.3%, occurring during the preceding five years. The median net worth of a family in 2010 was $77,300, compared to $126,400 just three years earlier because the too-big house that their government’s policies had encouraged them to over-invest in didn’t pay for itself. In 46 states, the poverty rates had increased during the previous five years, and the national poverty rate had been > 15% for the fourth year running. More and more families were and are dropping from the ranks of the USA’s once proud and confident middle class into “precarity”205.

One of the actors adversely affecting median household incomes is the scarcity of “good” jobs exacerbated by extended periods of unemployment including deliberate government shutdowns. More and

205 i.e., low pay, high blackmailability, intermittent incomes, etc., and, of course, the social consequences of poverty combined with relentless cost-of-living inflation. This fosters a pervasive sense of insecurity which why somuch of the advertising they see exorts them to buy various sorts of insurance.
more people are being forced to accept “gigs” rather than secure jobs that pay enough for their holders to achieve the same American Dream – real (not pretend\textsuperscript{206}) home and car ownership, etc. – that their parents (my generation) had enjoyed.

The picture isn’t much prettier with respect to the cost of the goods and services that they must consume. The Consumer Price Index (CPI) is currently the most relied upon figure for calculating the yearly inflation rate figures used to determine pay raises and pension benefits. According to Forbes, the USA’s Bureau of Labor Statistics (BLS) changed the way it calculates the CPI twenty times over the past 30 years, including new formulas and indices that separated the more volatile food and energy sectors (e.g., the cost of building nuclear reactors) to arrive at a “core inflation rate”. Those changes resulted in a significant dissociation between what the government reports as inflation rate, and what the middle class sees when buying the goods and services they need\textsuperscript{207}.

In 2014 Forbes declared, that “The CPI is not a measurement of rising prices, rather it tracks consumer spending patterns that change as prices

\textsuperscript{206} Nothing is really owned until the last payment has been made. The average US homeowner’s equity is currently under 50%.

\textsuperscript{207} For instance about 12 years ago I decided to replace my home’s too-weathered “engineered” wood fiber based lap siding with the same sort of cement stucco-over –polystyrene-foam board siding that renders Las Vegas’ Ceasar’s Palace so well-insulated. However, when I discovered that having a professional do it would cost me about $3.50/ ft\textsuperscript{2}. I decided to do it myself using a cheap ($15/50# sack) polymer-reinforced white “thinset” stucco, spread over 2” thick, 4 by 8’ foam boards (25cents/ft\textsuperscript{2}). The latter cost me $8/sheet then – they currently cost (Home Depot) $22.73/sheet. Similarly, the cost of roofing shingles has ~doubled since then.
change. The CPI doesn’t consider the falling value of money. If it did, the CPI would look much different.”

According to the BLS the CPI had gone up 1.6% that year, and had hovered between 1-4% for the preceding five years. However, if the inflation rate were calculated in the same way as it had been circa 1980, it would’ve averaged over 5% per year. For example, out-of-pocket healthcare costs had nearly doubled in the preceding seven years because our government’s increasingly special interest driven policies enable/encourage “health care providers” and drug manufacturers to charge whatever they can get away with.

Domestic energy prices have likewise dramatically increased. During the last decade, energy prices had more than doubled as our governments’ policies became increasingly ideological and counterintuitive. Energy and food cost inflation disproportionately affects the middle and lower classes. When I first arrived in Idaho Falls 40 years ago electricity was so cheap ($0.008/kWh) that most of its almost-new houses were simultaneously poorly insulated and “all electric” with resistive-type heating. Electrical power was cheap because President Roosevelt’s new deal dam building campaigns had rendered it so and the Northwest’s population growth hadn’t yet pushed power demand beyond its publicly built/owned system’s ability to satisfy.

ALICE, (the United Way’s acronym for Asset Limited, Income Constrained, Employed) which represents individuals and families who are working, but unable to afford the basic necessities of housing, food,

208 When pain and/or early death is the alternative, a service’s providers possess unusual leverage upon its customers.
child care, health care, and transportation), determined that nearly a quarter of a million of Idaho’s households – 40 percent – could not afford those needs in 2016 (ALICE 2018). While most Americans still think of the US as being a country of great economic mobility and opportunity, that mobility rate is now one of the developed world’s worst. In the US people whose fathers were in the bottom income quartile have a 40% chance of staying in that quartile and only about an 8% chance of making it to the top quartile, which is half of the average probability of moving up and one of the worst probabilities of the countries analyzed. In a country of equal opportunity, that would not be the case (Dalio 2019).

The childhood poverty rate in the US is now 17.5% and has not meaningfully improved for decades. In the US in 2017, around 17% of children lived in food-insecure homes where at least one family member was unable to acquire adequate food. UNICEF reports that the US is worse than average in the percent of children living in a food-insecure household (with the US faring worse than Poland, Greece, and Chile).

This chapter paints a pretty distressing picture of the USA’s middle class’s situation. Prospects for improvement are currently also pretty poor because the basis of their problems is causally connected with policies emanating from and firmly entrenched within their government at all levels. Because Congress still has the power to make laws and overcome vetoes and citizens can (in principle anyway209) still choose who leads them, it’s not just due to its current president’s (Trump’s)

209 Congressional district gerrymandering and the electoral college serve to disenfranchise millions of Americans.
mishandling of virtually everything relevant to addressing his country’s impending energy, social, and environmental conundrums. The Republican Party is dominated by people determined to restore economic feudalism and the Democratic Party overly politicizes science and hampers progress by championing both over regulation and unrealistic technical proposals. Capitalists typically don’t know how to divide the pie well and socialists typically don’t know how to grow it. When such economic polarity and poor conditions obtain, the USA’s leaders should pull together to reform the system. They are instead becoming progressively more extreme, fighting more rather than less resulting in today’s almost total deadlock on many important questions (Dalio 2019). This book’s subjects are too important to just ignore or wring our hands about. Everyone must become willing to do the homework required to understand the seriousness and urgency of their situation and properly evaluate the proposed technological fixes.

The person whose 1988 Congressional testimony sparked widespread awareness of both global warming and its causes within the USA, Dr. James Hansen, was critical of Hillary Clinton's intention to put 500,000,000 solar panels on rooftops across the USA: “You cannot solve the problem without a fundamental change, which means you have to make the price of fossil fuels honest. Subsidizing solar panels will not solve the problem. We have two political parties and neither wants to face reality. Conservatives pretend it’s all a hoax, and liberals propose solutions that are non-solutions."

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210 Jacobson et al. refer to their campaign as a WWS (wind water and solar)-powered “Solutions Project”. Other people not so heavily invested in its marvelous assumptions consider it a, “Non Solutions Project” (Beckers 2017). One of its tenets seems to be that a WWS-based Green New Deal could be implemented within ten (sometimes twelve) years. That’s absolutely impossible –
Unfortunately another of human nature’s quirks is that in today’s political environment, bloviating, uber-capitalistic, demagogues can employ the same “populist” tactics that Mussolini and Hitler did to seize command of government and therefore make things worse for everyone except their real “base” (other especially important people).

For example, former Washington Post Beijing correspondent, John Pomfret, recently pointed out (Pomfret 2019) that our federal government’s recent spate of charges against China’s leading telecoms company, Huawei, are a smokescreen for its real concern: U.S. security officials are afraid that Huawei’s technology will become the global standard for “5G”—a development that would have huge implications, both military and economic, to the global balance of power. This is an entirely legitimate fear for which America’s leadership has mostly itself to blame. The technology behind 5G is complicated, but not rocket science and depends mostly upon network density. A successful 5G network would require thousands\(^\text{212}\) of small “servers” scattered everywhere across the entire country. China has elevated the construction of such networks to the equivalent of the USA’s 1960’s-era moon landing project thereby outspending the U.S. by $24 billion since 2015. In other words, China’s advantage lies not in scientific genius but political will. That sort of contest favors nations capable of doing the

\(^{212}\)The reason for this is that a 5G network utilizes much higher electromagnetic frequencies than does a 4G system which renders its signals more directional, almost “line of sight”.

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every major transformation in how our civilization goes about powering itself has taken about 50 years & this one won’t be an exception (Rhodes 2018).
sorts of things at which China has come to excel and the USA no longer even bothers to attempt – public infrastructure building.\textsuperscript{213}

Fundamentally, it is a question of values. In the 1930s and ’40s, the general sentiment was that the nation would be better off if everyone had reasonably comparable electricity and telephone services. As a result, the federal government established a system of loans and grants to ensure universal access to those key utilities. To help, the FCC set up a system to charge businesses and urban customers slightly higher fees to subsidize the higher costs associated with bringing phone lines to rural areas. The question facing the U.S. now is whether it is willing to commit to providing affordable broadband service equitably to everyone regardless of who they are or where they live—many of us now don’t have access to or can’t afford even 3G service.

Pulitzer Prize-winning investigative reporters Donald Barlett and James Steele explain in their book, “The Betrayal of the American Dream” that what’s been happening to America’s middle class isn’t inevitable. It’s the direct result of government policy and it could be changed by government actions.”

The USA’s ultra-conservative Smoot–Hawley Tariff Act of 1930 implemented protectionist trade policies by increasing 900 import tariffs by about 40%. It worsened the Great Depression and thusly should instruct today’s political leaders. It doesn’t - President Trump has set off another trade war that’s apt to accomplish the same thing that Mr.

\textsuperscript{213} For example, every few years almost everyone in the USA has to submit to arbitrary, corporate-driven, and often disruptive changes in their personal computer’s word processing and spreadsheet applications (I’m so suffering now).
Hoover’s policies did (‘beggar your neighbor, beggar yourself’) and might lead to another world war.

Another little-known consequence of the USA’s trade war is that it is hurting academia as well as the people working in the sectors (e.g., farming) immediately hit by its tariffs. Here’s a note sent to me today (8/12/2019) from a high school friend who went on to become a professor in the University of Minnesota’s agricultural department:

“Many of us have had the rug pulled out from under our research. Most of our grant support came from "commodity group" checkoff funds which means we drew from a pool funded through the cash value of sales of a crop, corn, soybeans, wheat etc. Mine came from sales of Minnesota soybeans. Unfortunately, most of Minnesota's soybeans became exports to China. Because of the tariffs bout 60% of last year's crop is still in storage and any sales have been at a much reduced price.

The checkoff pool is pretty thin. In December I'll probably be terminating the researchers employed on my project unless a miracle occurs.

Roger Johnson, President of the USA’s National Farmers Union, is another person immediately affected by Mr. Trump’s approach to making America great again. According to him…–

.. “Today’s market uncertainties have halved net US farm incomes ”.;
(CNN interview, 8/13/19)

9.2 The USA’s over, under, and stupid regulations

One of the things stifling US job growth is the overreach of special interest-driven governmental regulations due to the way that the people
we’ve chosen to represent us (Congresspersons) have decided to fund their political campaigns\textsuperscript{214}. In 2013, a U.S. Chamber of Commerce survey showed that 74\% of small businesses were positioning themselves to slash hours, lay off workers, or both primarily due to how the USA had gone about implementing its “Affordable Care Act”\textsuperscript{215}. Nearly 300 large companies admitted to reducing hours for their employees in order to get below its mandated 32 hour/week threshold. That’s the result of just one piece of poorly thought-out, special interest (health insurance, pharmaceutical, and medical industries\textsuperscript{216}) campaign contributor-driven, legislation.

In 2012, the USA’s House (of Representatives) Committee on Oversight and Government Reform published a report illuminating the role that

\begin{itemize}
  \item For example, the 2010 Republican-pushed/won, “Citizens United” legal battle overturned the McCain–Feingold Act which had prohibited corporations from funding "electioneering communications" and thereby effectively removed limits to the degree that they could help elect business friendly candidates. "Government by organized money is just as dangerous as Government by organized mob." Franklin D. Roosevelt
  
  \item Aka “Obamacare” to the Congresspersons that had ensured that the ACA would end up doing that, not by President Obama himself. He would have much preferred a single payer system which would have served everyone equitably and reduce total costs, not just shovel more money into the same special interest dominated system.
  
  \item In 1965, the US federal government created Medicare and Medicaid to provide health care services for its elderly and poor. These programs currently provide some degree of health care for 38 percent of its total population. Unfortunately, the loopholes that were deliberately left in that legislation plus the fact that they didn’t cover everyone means that the USA’s mostly-privatized health care system has become ridiculously expensive, leaving 41 million US citizens underinsured and 28 million with no coverage at all. A single payer (“Medicare for All”) system would foster real competition, provide health care to everyone and, by taking price-setting out of the hands of insurance companies and for-profit hospital managers, drastically reduce administrative, drug, and professional care costs. It would also remove a huge overhead burden from both doctors and employers which, in turn, would encourage job/business growth.
\end{itemize}
government has played in suppressing job growth. It concluded that, "Many regulations and legislation – both existing and proposed – exacerbate the uncertainties created by today’s volatile economic environment. Virtually every new rule/regulation has an impact on recovery, competitiveness, and job creation.” President Obama’s own Economic Advisory Panel came to the same conclusion, saying that “regulations are harming businesses and job creation.” That panel went on to suggest several measures that could be implemented to quell the expansion of such job/economy-destroying rules and regulations.

No other sector of the USA’s economy is as much affected (suppressed) by bureaucratic overreach as is nuclear power. The chief impediment being its Nuclear Regulatory Commission which is empowered to determine whether any real or proposed activity involving “special materials” falls under its purview and then charge whoever wants to do anything with them a fee for what it decides that its licensing and oversight activities are worth (see NRC 2019). It is also notoriously slow in responding to requests for such help/advice/permissions, which holds up projects raising overhead costs. That’s one of the realities that caused DOE’s NE decision makers to try to substitute “modeling” for experimentation which, of course, didn’t work out.

Periods of rising middle class income coincide with periods of economic expansion and growth like those prevailing from several years before the beginning of WW II up until about 1970. During that time the USA’s tax system prevented the super-rich from hogging the majority of the nation’s wealth (top marginal tax rates were >90%) and its government employed that money to embark upon the massive infrastructure-building projects that quickly “made America great”- Hoover Dam and the string of others that tamed the Mississippi and Columbia, the Tennessee Valley Authority, our interstate highway system, etc., etc.,
while ensuring that it would be cheap/easy for its citizens – especially its military veterans - to buy homes and get low cost educations all the way up through college. During that time, our government won that biggest of all wars (yet) and neither micromanaged the projects that its taxpayers and bond buyers were funding nor imposed efficiency-killing rules and laws. To the contrary, that government (not today’s) put people in charge that were willing to insist that its contractors did the job that were being paid to do – not decide for themselves what that job should be. That’s one of the reasons why the AEC’s NRTS in Idaho, was able to design, build, test, and then decommission >50 nuclear reactors and repeatedly recycle the fissile (highly enriched uranium) so-used during its first two decades.

The other reason is that failure has become expected (acceptable) within the DOE’s nuclear complex because (almost) everyone within it knows that it’s become almost impossible to do anything that’s either “risky” or inconsistent with extant political drivers. Consequently, even though DOE now spends more money (about $32 billion/year) and the need for such work is greater than it was six decades ago, it has become incapable of either doing or managing the sorts of projects that the AEC and its contractors quickly accomplished back then.

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217 DOE no longer devises its own technologies, it chooses between the offerings of entrepreneurial contractors. NASA now does the same thing – in both cases it’s a tacit admission that the government no longer entrusts itself to do such things. The leadership of each of the DOE’s national laboratories is chosen by its M&O contractor’s top management (e.g., Bechtel’s CEO), not DOE. Additionally, that contractor’s personnel, not DOE’s, make most of the decisions at each site based primarily upon how much money can be made rather than how such efforts further that site’s mission. The consequence is that a DOE contractor can and usually does, receive almost 100% of its potential “award fee” while failing (again) to accomplish that site’s nominal mission – hence INL’s and Hanford’s interminable reprocessing radwaste boondoggling.
Mankind’s history is littered with examples of once-dominant nations that had overreached with poorly thought-out plans and policies which crippled their economies and eventually led to collapse due to gross inefficiencies. Great Britain’s current “Brexit” situation is apt to lead to that conclusion and the USA seems hell-bent upon following it down the same rat hole.

However, as much as both over and stupid regulation must be curbed, there are some things that do need “centralized planning” among which are those upon which the ultimate success of any technological civilization depends – the educational, health care, and energy systems that enable its people to succeed\(^\text{218}\). The real problem is bad rules and regulations, not their number.

Regulation – about the only positive thing I’ve seen come out of Mr. Trump’s federal government so far is that some of its sillier laws, rules, customs, and regulations are being reviewed; e.g., the USA’s approach to labeling its radwastes. If such laws, rules, customs, and regulations aren’t replaced with equally inane ones (to be determined) that certainly would be a worthwhile achievement. President Trump & his successors must encourage research by cutting the regulatory red tape crippling innovation in any/all nuclear fields. A company wastes up to ten years and $100 million dollars in fees to obtain the Nuclear Regulatory Commission (NRC) permits necessary to conduct research into critical advanced nuclear technologies. The deleterious effect of the USA’s

\(^{218}\) For instance, the reason that the USA’s citizenry can continue to drive huge distances in huge cars is that their government absolutely insisted that those vehicles become far more efficient than they were circa 1975. Mr. Trump and his supporters want to eliminate such meddling with their country’s business sector’s technical decisions.
regulatory burden on its energy innovation and baseload security cannot be understated. Red tape has driven ThorCon and Terrapower’s people and investment dollars to research facilities situated in Indonesia and China, respectively. Streamlining the permitting process for advanced nuclear research will keep atomic energy leadership and jobs here in America.

However, it also seems that most of the people Mr. Trump has chosen to head his science/technology related agencies are more determined to undermine them than anything else; i.e., insist upon throwing babies out with the bath water. For example, in 2018 Republican Sean Sullivan, then chairman of the Defense Nuclear Facilities Safety Board (DNFSB - an “independent” panel charged with protecting workers and local stakeholders at DOE’s nuclear weapons facilities) told Mr. Trump that he recommends abolishing that group, despite recent radiation and workplace safety problems at some of those sites. The main reasons for this were: 1) it’d save taxpayers about $31M/a; 2) DOE’s contractors & their Congressional supporters don’t like their decisions to be second-guessed; and 3) like the other groups that oversee DOE’s sundry activities (e.g., Nuclear Waste Technical Review Board (NWTRB) and Site Specific Citizen Advisory Boards), its recommendations are considered to be “advisory” (i.e., just window dressing) – it doesn’t actually have to act upon them.

Some of his government’s agencies should become more, not less, proscriptive/powerful: for instance, almost everyone would be better off if the US were to adopt just one measurement system (metric) and limit the number of screw/bolt head choices that manufacturers can use. Why do we pay for a “NIST” that’s not empowered to set standards? Any house being sold should come complete with blueprints informing their purchasers where its pipes, wires, septic tank etc. are located. At the
very least such information should be freely available from the governmental agency paid to issue its building permit.

As far as the future is concerned, the only way that today’s internal combustion engine powered cars could be replaced with 100% electric vehicles (BEVs) is if governments dictate a “standard” battery pack configuration that could be as quickly switched at refueling stations as we can now pump five gallons of gas into a tank.

Health – today’s tremendously overhead-burdened health care system could be rendered much more efficient, cheaper, and effective (fairer) by simply adopting a single-payer “medidental” care system for everyone and eliminating the 20% coverage gap currently serving to foster most of today’s privatized “senior insurance” scamming. Doing so would permit business owners and their employees to concentrate upon running those businesses – not worry about or compete with each other about “benefits”. People in the healthcare sector should be providing health care services – not wasting most of their time trying to please shareholders, lawyers, hospital MBAs, and insurance company CEOs. Making free enterprise work as it should will require reducing bureaucratic overhead thereby allowing individuals to focus upon running their businesses not “compliance”. Currently, many US

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219 My experience with “socialized medicine” came during the two years that I served as an enlisted “night man” at Ft. Ord Army Hospital – we did a good job of taking care of people, felt good about it, and no one had to worry about being sued or paying for anything.

220 INEL/INEEL/INL’s employees were (are?) constantly reminded that “compliance” is their employer’s overriding mission.
citizens are locked into terrible jobs because they can’t risk losing their health care benefits.

Leveling the playing field between “small” and large businesses will require cutting business-related red tape, simplifying the tax code, ending loopholes, and (maybe\textsuperscript{221}) reducing the overall tax rate. Currently, in spite of the fact that the USA’s large businesses are nominally more heavily regulated, in practice they pay less taxes than do small ones because they can afford to out/off source more things and pay for a horde of accountants/lawyers and political campaign donations\textsuperscript{222}. Unions should be encouraged. Sweden has industry-wide unions that negotiate wages and therefore neither has nor needs minimum wage laws. Germany’s big businesses have worker councils in which everyone comes together to cordially discuss how things should be run. Japan’s auto industry did/does the same thing which is one of the reasons why its cars are so well designed, well made, and affordable.

Education – everyone should be given a fair chance of getting whatever education they’re both interested in and capable of absorbing\textsuperscript{223} from

\textsuperscript{221} “maybe” because replacing the USA’s dysfunctional health care system with one that better serves its people will require that some of its expenses be paid with their taxed, not their after-tax, dollars. Their total out of pocket expense would surely be less but they would no longer be free to choose between premature death/misery and supporting a “socialistic” heath care system that might prove to be even more terrible than social security!

\textsuperscript{222} That’s surely the reason that the USA’s current businessman president refuses to release his personal income tax information.

\textsuperscript{223} This means free to anyone ready, willing, and able to learn what must be learned to master worthwhile subjects – no more “parapsychology” majors, social promotions, and having your parents buy you into one of the “best” schools (“... today, FBI Authorities say its operation, dubbed Varsity Blues, uncovered 33 parents described as a ‘catalog of wealth and privilege’ had collectively paid $25 million to a college admissions counsel who, who had pleaded guilty and
kindergarten to PhD for free. Civics lessons should become a much more important part of that education. A year or so of public service should also become part of everyone’s education. The “draft“ used to serve that purpose for young US males not rich or “connected” enough to suffer from bone spurs. Some of those draftees learned skills/trades while so-serving that subsequently became their means of livelihood^224. Today’s approach to school funding encourages/enables the super-rich to send their children to prestigious private schools and colleges while simultaneously doing whatever they can to short-change other peoples’ kids. It’s not really good for anyone except the people selling such high-end services.

Energy – as I’ve tried to teach in this book, the amount of useful energy serving each person determines his/her life style: happy/sad, rich/poor, free/entrapped, secure/precarious…. That energy must be “clean”, cheap, reliable, genuinely sustainable, and sufficiently abundant to

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^224 During the Vietnam War while I was completing the US Army’s basic training, its leadership decided that I could best serve the nation by becoming a hospital laboratory technician. The ensuing 3-4 month, on-the-job educational experience at Fort Ord’s hospital was the most efficient that I’d ever experienced (I’d been drafted out of graduate school and already had a MS in chemistry). I soon became one of the lab’s three “night men” entrusted with handling any of the STAT requests that might come in during the sixteen hours each day when no one else was there. Of course, as soon as my two years were up, I was no longer “qualified” to do such work anywhere else in the USA because each individual state allows its already-licensed civilian med techs to decide who might compete with them (that profession is one of the USA’s far-too-many “closed shops”).
provide everyone with a lifestyle comparable to or better than that of today’s average European. That combination of characteristics could realistically be realized only with a properly implemented nuclear renaissance – not with biofuels, windmills, solar panel/towers or more-of-the-same unsustainable nuclear reactors. This means that implementing this book’s version of Goeller and Weinberg’s “Age of Substitutability” represents a way for the next couple of generations of US citizens to do for themselves the same sorts of things that Franklin Roosevelt’s “new dealing” empowered their great grandparents to do. DOE’s management culture fosters poor team player harassment which stifles innovation and enables the people nominally responsible for making such a renaissance possible to ignore that mission to better serve more immediate political/cultural/financial/personal interests.

225 In many cases simply asking “why” when unethical and/or unreasonable actions were observed resulted in harassment and shunning. I survived (but did not thrive) for over a decade after I’d started crossing that particular Rubicon (INEEL 1997, INEL 1996) because I was careful to initially submit my observations/suggestions up through the proper chain of command while reminding everyone that doing so is exactly what the folks who had given us our “ethics” training” told us was the right thing to do. When I first began to wonder about how I should respond to some of the things that were happening, I had the good fortune to stumble upon a book, “The High Priests of Waste”, written by the US Federal Government’s most successful defense-contracting system’s whistle blower (Fitzgerald 1972). When he was very predictably fired for rocking the US Air Force’s boat too much, Mr. Fitzgerald appealed to the Civil Service Commission and subsequently won both reinstatement and promotion to the Senior Executive Service where he spent the next thirty years reminding his bosses that their favorite “pet elephants” (“too big to fail” contractors) were supposed to abide by the same rules that everyone else had to. Nevertheless, whenever those pets (e.g., Lockheed) were going through lean spells between big defense contacts, their close friends in high places continued to make sure that they could make a few bucks managing little things like the USA’s national laboratories. For an up-to-date example of how that continues to serve taxpayers see https://www.rt.com/usa/451098-hanford-nuclear-lockheed-lawsuit
9.3 Why we need a Nuclear Green New Deal

The solution to the USA’s malaise is relatively simple and should be recognized by everyone from the chairman of the Federal Reserve to the AFL-CIO’s leadership. In fact, that labor organization perhaps worded it most succinctly in a piece titled, “How do we fix the U.S. economy?” They declared that the first step must be “to put America back to work because high unemployment keeps wages down. Our goal should be ‘full employment’, meaning everybody who wants to work should be able to find a decent job.”

The Green New Deal has recently become a big part of policy debates in the US largely due to the efforts of Rep. Alexandria Ocasio-Cortez (D-NY), the youngest woman to be elected to the House of Representatives and expected to run for president in 2024. Her ambitious proposals address environmental issues that 60% of Americans say are already affecting their local community and promises to tackle economic inequality through the creation of unionized high-quality jobs. The Green New Deal has also been helped by the youth-oriented grassroots outfit Sunrise Movement, which organized a protest at Sen. Dianne Feinstein's office in February 2019.

That same month, Ocasio-Cortez and Sen. Ed Markey (D-Mass.) introduced a 14-page nonbinding resolution calling for the federal government to create a Green New Deal. That resolution has over 100 Congressional co-sponsors, including several Democratic presidential candidates.

While the ideas behind a Green New Deal and the threat of climate change have been known to politicians for almost two decades, it represents the most detailed plan yet to transform the economy presented
to the American people, even though it is itself extremely vague and more a set of principles and goals rather than policies. The Green New Deal resolution also doesn't mention how the U.S. government (meaning us) which is already $22 trillion in debt would pay for it.

In short, it states that the U.S. must take a leading role in reducing emissions because it is both technologically advanced and responsible for a disproportionate fraction of total anthropogenic greenhouse gas emissions.

The very real existential threat to the planet posed by the continuation of “business as usual” renders the Green New Deal’s mission statement hard to either ignore or dismiss. However, critics have called it too socialist, too extreme, and/or too impractical. I concur with only the last of those criticisms because achieving its goals with today’s suite of politically “acceptable” renewable energy sources would be impossible.

I’m hoping that the current crop of liberal presidential candidates lobbying for a “green new deal” take another look at the assumptions underlying their apparent faith in Mark Z. Jacobson et al.’s fine-sounding but technically unrealistic alternative energy schemes. Protecting the environment and lifting the developing world out of poverty are progressive causes which may cause the millennials and Gen X’s to rethink the values that their boomer parents haven’t reexamined since they grooved at the Doobie Brothers’ “No Nukes concert” forty years ago. Most of them would be delighted to don blue MAGA hats if the technologies underlying the Democratic party’s “green” proposals had a better chance of actually working. It’s possible because both psychology and politics can change quickly. As the enormity of the Anthropocene’s climate crisis finally sinks in and the hoped-for carbon savings from politically correct renewables aren’t realized, a properly implemented nuclear fuel cycle could become the “new green”.
I also hope that the nuclear establishment’s ayatollahs become willing to question their assumptions and dictates. Nuclear power should, could, and must become “renewable, not just a temporary bridge to a future powered with “all of the above” except nuclear energy.

Electrifying the USA’s residential, industrial, agricultural, and transportation sectors via the development and implementation of a appropriately scaled and genuinely sustainable nuclear renaissance would provide millions of genuinely good jobs/professions for its citizens – not just more service-type gigs.

Chapter 10. Suggestions for improvement

"The first thing we do is kill all the lawyers"
William Shakespeare

10.1 Stop bean-counting

The way that DOE goes about labeling, performing and assigning costs to its activities often serves as “the kiss of death” to perfectly reasonable – often the most reasonable - ways of addressing its nuclear-related technical problems. For example, because DOE chooses to refer to its Hanford waste management boondoggle as a “vitrification” project, in many people’s minds, that technology has become almost impossibly expensive/difficult to implement. That’s baloney, real glass is often too cheap to recycle and melter off gas is easy/cheap to

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226 For instance, circa 2002 the “overhead” cost assigned to any time that an INEEL technical employee (scientist or engineer) charged to a project was typically 3-5 times his/her hourly salary-plus-benefits compensation rate. In my case, that resulted in my efforts costing US taxpayers $180-$300 per hour. That was a relatively modest figure/rate because, by that time, I was no longer receiving “average” annual pay raises.
clean up. Similarly, DOE’s assertion that it would be billing its YM repository’s prospective customers (at least INEEL’s) at a rate that eventually topped ~ $800,000/m³ also made radwaste “disposal” seem ridiculously expensive. How much should it cost to dig one cubic meter’s worth of hole in “soft” rock with a second-hand tunnel boring machine & then chuck something into it? Its experts have similarly managed to demonize both calcination and incineration.

10.2 Really “reorganize” DOE

Energy has been the entire world's biggest “real" business

for well over a hundred years and devising a viable substitute for the ways that we’ve gotten used to generating it could make America great (and rich) again. Consequently, DOE should no longer be entrusted with the management of the USA’s nuclear engineering/scientific development efforts because that undertaking is too important to entrust to an organization that can’t decide what its mission is (“all of the above”?) or how to go about accomplishing it. Its NE division shouldn’t just be reorganized again because much of what it does doesn't really have much to do with developing a sustainable nuclear fuel cycle and its topmost leadership has proven itself to be unwilling to either change or lead.

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227 “real” as opposed to service industries like marketing several times-marked-up Chinese-made goods, banking, insurance, regulation, litigation, and advertising.

228 e.g., “all of the above” is a slogan not a plan. The purpose of a nuclear reactor is to generate power, not to be “small”, “idiot proof”, “manage transuranic waste”, or complement more politically correct (wind, solar, biofuels, etc.) ways of generating it.

229 Reorganizations generally just shuffle management personnel sideways to equivalent pay-slots where they’re apt to be equally or more incompetent. In the DOE Complex, some of them
Unlike Mr. Trump’s deliberate efforts to create a government-wide kakistocracy, DOE’s appointed top dogs usually don’t deliberately set out to run their bailiwick in that fashion – its deeply engrained management culture’s momentum accomplishes it naturally.

Every assumption/rule/law currently engendering foot-dragging on efforts to address Mankind’s key technical issues must be critically examined and appropriately modified. One such assumption is that nuclear power isn’t “renewable”. It could be and must become so, which should constitute our federal government’s NE R&D top dog’s vocation, not continuing to help his/its “industrial partners” develop/sell whatever they feel is more “realistic” over the short haul. If he/she wants to actually solve mankind’s long term energy conundrum, he/she must become willing to take his/her employees’ blinders off and empower them to do the necessary experimentation. Nuclear weapons proliferation is a political, not technical problem because any sort of reactor must have fissile within it which, in principle, could be “diverted” and somehow misused. Again, we voluntarily accept the risks of traveling in cars and airplanes even though they are very real and much greater than are those posed by any sort of realistically managed nuclear fuel cycle. Likewise, nuclear waste management’s issues are “pretend” issues that would be easy/cheap to deal with if our leaders & their cadre of good-team-playing technical experts really wanted to.

end up filling slots supposedly reserved for that site’s “Fellow” and “Consulting” engineers/scientists.
10.3 Reevaluate priorities

Next, any clean energy source’s value should be based upon the degree it could serve mankind’s long term needs, not upon how much “capacity” it might provide. If adding such capacity to an energy suppliers’ portfolio doesn’t enable replacement of their fossil fuel powered generators, its “value” should approximate zero, not considered especially high due to special subsidies or warm fuzziness.

A hefty carbon tax should be levied upon any fossil fuel that’s apt to become GHG. James Hansen has suggested that most\textsuperscript{230} such money should be returned to taxpayers/customers via the IRS rather than given to special interest driven/funded politicians to spend as they wish. I agree that this would probably be the fairest and most effective way to affect the necessary changes.

A U.S. GHG reduction policy should create a level playing field in which all real and proposed energy production technologies can compete in an open marketplace conditioned by legislated CO\textsubscript{2} emissions goals. A CO\textsubscript{2} (“carbon”) price for all carbonaceous fuels without long-term subsidies or other preferential policy treatment would be the most effective way to achieve it.

The NRC should oversee the operation and licensing of existing reactors, not dictate how the laboratory and pilot plant experimentation necessary for reactor development is to be done. Its current rules, regulations, lack/level of technical expertise, mindset, and mode of

\textsuperscript{230} Some of that tax money should fund NE-R&D specifically dedicated to devising a sustainable nuclear fuel cycle.
financing\textsuperscript{231} constitute one of that industry’s most formidable “barriers to science”. For example, one of the chief drivers/excuses for DOE’s grossly inefficient separations-based reprocessing waste management schemes is a several decade old NRC opinion which stated that HLW from which a “maximal effort” had been made to remove its high components\textsuperscript{232}, no longer had to be considered HLW.

Any such rules/opinions dictating actions should specify definite toxin/radionuclide concentration limits, not adjectives.

Whatever organization ends up in charge of developing/implementing a sustainable US nuclear renaissance (I’d recommend a new branch of the military\textsuperscript{233}) should eschew the personnel management philosophy reflected throughout the DOE’s Nuclear Complex because it destroys esprit de corps, inhibits creativity, and fosters cynicism.

For instance, at INEL/INEEL/INL although everyone “coming on board” during a specific time was “guaranteed” a set of work related rules and benefits, every succeeding contract change encouraged the new contractor inheriting the management of both that Site itself and its

\textsuperscript{231} Among the contextual benefits that China, Korea, and Japan reactor builders enjoy relative to Western countries is that the regulator is paid by the government, not the vendor or developer.

\textsuperscript{232} Especially “high” radwaste constituents include \textsuperscript{90}Sr, \textsuperscript{137}Cs, TRU (especially Pu) and in some cases, \textsuperscript{99}Tc and \textsuperscript{129}I.

\textsuperscript{233} The USA’s two most successful nuclear engineering projects were managed by uniformed (not retired) military officers (Groves and Rickover) who weren’t confused about whom they were working for or what their mission was. One caveat I’d add though is that it should become absolutely verboten (result in permanent loss of all benefits, honors, pensions, etc.) for any such person to “retire” and go to work for a contractor having anything to do with that mission either directly or as a lobbyist.
employees to chip away at those guarantees and keep the money for itself. The excuse proffered by the Idaho Site’s management whenever anyone screwed up enough courage to point that out was, “that’s the way that things are going everywhere else in good ‘ol USA – if you don’t like it, you are more than welcome to quit because there’s lots of fresh young college grads out there clamoring for any sort of ‘good’ job these days”.

That’s no way to convince the best and brightest of any institution's employees to do their best to help make it succeed.

Another consequence of a work culture that fosters cynicism is that many of its employees lose whatever enthusiasm they may have originally had about nuclear power itself. If a researcher is consistently forced to act in ways that would serve to render a sustainable nuclear renaissance impossible (e.g., design reactors that would maximize the waste of startup fissile), he/she eventually becomes technically incompetent regardless of what his/her official credentials or title happens to be.

During the years that I worked there most of Chem Plant’s employees were viewed as cogs in a machine that implemented procedures. It worked fairly well up until the time that its primary mission changed from reprocessing small lots of miscellaneous spent reactor fuels to devising “uniquely cost effective ways” of managing its radwastes. Research can’t be proceduralized because it requires creative as well as collaborative talents. If an institution’s leadership really wants to address a new technical problem, employees motivated to both learn and grow would much more valuable than those who just want to fit in.

A good sized chunk of money should be devoted to building a test reactor similar to the one depicted in Figure 26 – the one proposed by the folks managing the EU’s EVOL (MSFR) program six years ago (Lucotte 2013). It’s a relatively but not trivially small reactor (about one
cubic meter core volume and up to about 100 MW thermal – enough to power a small city during tests) which could be used to test/develop almost any kind of “fast” molten salt breeder/isobreeder & its attendant fuel cleanup/reprocessing/waste treatment system.

Figure 26: Generic FS MSR test reactor (core volume roughly 1 m³, heat generation up to 100 MW, its “reflector” volume/tank could either contain a molten bismuth (or tin/lead) neutron reflector or a fertile-containing molten blanket salt.

The goal of the studies performed with it should be to devise something that’s simultaneously sustainable (CR>=1), maintainable, and affordable, not just make work for experts doing more of whatever they’re already comfortable with.\textsuperscript{234} DOE’s topmost NE R&D experts

\textsuperscript{234} For instance, a great deal of work has recently been done at ORNL to “assess the feasibility of replacing the conventional uranium oxide (UO\textsubscript{2}) fuel of the existing fleet of light water
are still refusing to consider building a test reactor capable of guiding any such effort. For example, starting in 2015 INL began putting together a list of options for a brand-new test reactor optimally capable of addressing DOE’s sundry R&D goals. That document was finished two years later (Petti et al 2017) – it listed criteria & characteristics of four different possible alternatives none of which was any sort of fluid-fueled (molten salt) reactor, but didn’t yet reveal the “winner”. Two years later, that program’s director actually did identify it (the “Versatile Test Reactor” (VTR)) at a conference in San Diego (Pasamehmetoglu 2019). As anyone familiar with how DOE goes about making such decisions might expect, the VTR is just another tiny (especially small & modular) sodium-cooled, pool type, fast reactor – basically the same thing that INL/ANL has been “studying” since circa 1949 & of course, poorly suited for studying anything else.

APPENDIX XIII goes through a specific example of the sorts of questions that a little test reactor like Fig 26’s could answer.

When one or more of the concepts so-investigated meets those criteria, moving it/them to full commercial scale will require additional paradigm shifting because the current incentives for private investments in large scale demonstrations are too weak (the valley of death) and the government’s track record in managing large demonstration projects is too poor (the technology pork barrel). Both recent literature (Nemet

reactors (LWRs)with accident-tolerant fully ceramic microencapsulated (FCM) fuel” (Powers 2013). The fuel in question consists of the NGNP’s project’s TRISO kernels in which their UO₂ has been converted to uranium nitride (actually UC\textsubscript{0.25}Si\textsubscript{0.75}) and then embedded in silicon carbide instead of pyrolytic graphite. Such fuel would be difficult and expensive to make, virtually impossible to reprocess, and the reactor itself would be little or no more fuel (uranium) efficient than are today’s LWRs.
2018) and the results of over 500 case studies indicate that policy makers should emphasize/support: prioritizing learning, iteratively upscaling, tolerating minor setbacks, engaging the private sector, knowledge dissemination, and encourage demand pull by removing bureaucratic barriers and giving the concept full credit for its strengths/virtues relative to other renewable energy sources.

A big problem with MRS development is that most of the R&D powers-that-be (invariably engineers) don't seem to realize that a genuinely sustainable nuclear renaissance would be "a chemist's reactor" and therefore don’t pay enough attention to chemical issues – things tend to get “engineered” before the necessary science is done. That’s one of that reasons why “unobtanium” has become so necessary (the other reason is that insufficient attention is paid to rendering reactor concepts easy/cheap to maintain). Most of DOE's radwaste management gurus are similarly blinded which is why the part of its overall mission that they are responsible for didn't recognize that using a paper-based “kitty litter” liquid adsorbent to sop up decay heat-generating, nitrate-containing radwastes might lead to the "issues" that shut down DOE’s $19 billion Waste Isolation Pilot Plant (WIPP) and backed-up its cleanup activities elsewhere for over three years (WIPP 2019).

I also feel that the US federal government should again become willing to compete with “free enterprise” in the electricity generation/supply

235. Two people at the Manhattan Project’s “metallurgical laboratory”, Harold Urey, isotope chemist, and Eugene Wigner, the Hanford reactors’ engineer/physicist designer, both Nobel Prize winners, argued whether reactors ought to be considered mechanical engineering devices or chemical engineering devices. Both ended up agreeing along with their then, junior colleague, Alvin Weinberg, that power reactors ought to be considered chemical devices in which solid fuel elements were replaced by liquids.
business, especially nuclear-type power. There’s nothing really radical about this proposal because the “new deal” dams that enabled the USA to become “the arsenal of democracy” during WW II, were government built, owned, and managed. Nuclear power generation must be done especially “right” meaning that it should be provided by a mission-dedicated institution run like a US Coast guard managed by someone like Admiral Rickover, not by typical US businesspersons or DOE project managers.

Chapter 11. Conclusions

The discovery of nuclear energy represents one of the largest technological leaps that humanity has ever made. It is equaled only by fire, electricity, and heat engines. Those technologies were not just new tools or simply another way of doing the same things. They rewrote the rules at a fundamental level and couldn’t be understood using the same terms and rules extant before their invention. Collectively they made today’s civilization, industrialization, and mechanized transport possible.

Climate change is currently contributing to a man-made “sixth extinction” comparable in scale to that which killed off the dinosaurs

\[\text{236 In 1971 Alvin Weinberg first used the term "Faustian bargain" to describe nuclear energy:} \]
\[\text{“We nuclear people have made a Faustian bargain with society. On the one hand we offer—in the catalytic nuclear burner (i.e., the breeder)—an inexhaustible source of energy. Even in the short range, when we use ordinary reactors, we offer energy that is cheaper than energy from fossil fuel. Moreover, this source of energy when properly handled is almost nonpolluting. Whereas fossil-fuel burners emit oxides of carbon, nitrogen, and sulfur... there is no intrinsic reason why nuclear systems must emit any pollutant except heat and traces of radioactivity. But the price that we demand of society for this magical source is both a vigilance from and longevity of our social institutions that we are quite unaccustomed to.” Expressing such sentiments in a public forum is the reason that Nixon’s AEC downsized him.}\]
(Kolbert 2014). A recent paper published in the Proceedings of the National Academy of Science (Sherwood & Huber 2010) points out that the continuation of present trends could cause humans to also become “extinct” over much of their current range by 2100AD237.

The most realistic way for humanity to kick its increasingly destructive addiction to fossil fuels would be to implement a nuclear renaissance capable of meeting the energy needs of a bigger, cleaner, and much fairer future world. Because “affordable” uranium could fuel one implemented with today’s reactors for under one decade, it must employ breeder-type reactors with close-coupled fuel reprocessing systems. Since the majority of future anthropogenic greenhouse missions will be generated by a developing world that can neither afford to overpay for energy nor undertake a “Manhattan Project” to develop a sustainable nuclear fuel cycle, today’s technologically advantaged world has the responsibility to do so. Because molten salt reactors are uniquely well suited to addressing these problems, research seeking to realize their potential should receive top priority. Unfortunately, most of the world’s political leaders choose to address causes that are less controversial and more immediate than is the development of a sustainable solution to what many of them apparently still consider only a “future problem”.

237 Sherwood & Huber’s argument is based upon scientific realities, not polled opinions. Human core temperatures must remain at about 37°C and, even while resting in the shade, we generate ~100 W of metabolic heat that must be dissipated via some combination of heat conduction, evaporative cooling, and infrared radiative cooling. Net conductive and evaporative cooling can occur only if an object (human) is warmer than its environment’s wet-bulb temperature which is rising world-wide due to enhanced oceanic evaporation. If the wet-bulb reading gets above 35°C, the human body can no longer cool itself off, even if fully drenched with sweat & standing in front of a fan. This is when serious health problems like heat stroke set in, for even young and healthy people not rich enough to pay for air conditioning.
A properly implemented nuclear renaissance would mean that we would no longer consider energy to be a limiting resource. We would no longer have to conserve it because it could be produced in unlimited quantities by “burning” the almost infinite amount of natural actinides present in common rocks and seawater. We would also not have to destroy the world’s remaining wild places and almost every creature living therein just to generate the energy required to keep our civilization going. The natural world wouldn’t have to do anything beyond serving as a passive heat sink for reactor cooling which service would heat our environment far less than does today’s fossil fueled approach to energy generation.

Where that renaissance might take us is beyond our imaginations. With that would come backlash. For one thing, most people just don't understand the magnitude of the necessary changes. Furthermore, nuclear power is scary, because it's a form of energy that very few people understand, but what they do “know for sure” is that it could be harmful if misused.

Change is always tough for grownups to accept. Our great, great grandparents were probably hearing things like…

“Electricity? Are you kidding? That’s basically just letting lightning into your home. I think that kerosene (whale oil?) lamps work just fine. Electricity is unnecessary. Can't it kill you? That deadly force, inside your home? We don't need this. Running those wires is costly too, and so damn expensive to build this all out.”

It’s likely that when the use of fire was first considered by a tribe of our pre-sapient homo ancestors, some of them didn't want it. All they knew is that they’d heard about how fire had destroyed a forest and that someone had been burned when they’d tried to “divert” some of it.
Today’s remaining fossil fuels constitute a very much finite resource and Mother Nature won’t replace them within a time scale that’s relevant to our species. Since most of the “easy” such fuel has already been mined, they are now and will become more expensive as time passes. Unless something very much like the scenario described in this book comes to pass, people in poor counties will remain poor and the “middle class” of the richer ones will begin to riot over cost of living increases (especially fuel costs) as is currently happening in France, Mexico, Venezuela, Zimbabwe, Haiti, and Jamaica. Both the obtaining and burning of fossil fuels pollutes the world that we all must share. Because those resources also represent the most efficient source of the raw materials necessary to make the plastics, lubricants, insulation, fabrics etc., that render life pleasant in first world countries, we must quit wasting them just to generate energy services. Wind and solar power backed up with plenty of batteries is suitable for niche applications like powering the “cabins” back in the wilderness that the super-rich occasionally helicopter-in to visit. They are unsuitable (too unreliable) for powering the factories, ships, trains, cars, trucks, farm and mining machinery, etc., that have brought us the benefits of today’s technological civilization which means that must devise something that can. Today’s nuclear fuel cycle isn’t scalable (fuel limited) which is why I’m trying to convince folks that we must develop/implement a genuinely suitable replacement and that doing so is possible.

The USA’s millennial generation and their successors are currently experiencing economic uncertainties/anxieties similar to those which haunted their great-grandparents during the 1930s. The reasons for their distress are basically the same foibles of human nature that brought on both the “great depression” and WWII. We/they can no longer afford to allow the tax-supported institutions and experts charged with the responsibility of solving our technical problems to “grow their
businesses” by consistently choosing to discharge their responsibilities in grossly inefficient and self-serving ways. DOE’s reprocessing wastes could be properly disposed of quickly and cheaply, which feat would demonstrate that a nuclear renaissance’s “waste issues“ do not constitute just another excuse for not implementing one. The USA’s recent failures in most things “nuclear” other than providing our military’s leaders with thousands of bombs and generating some relatively cheap, clean, & reliable electricity for its citizens, aren’t “disasters” because nobody’s been physically injured by them or is even apt to be. However, those failures/boondoggles continue to generate easily documented and hard to refute arguments for why a US “nuclear renaissance would be both environmentally impactful and prohibitively expensive” and thereby serve to prevent the USA from doing what must be done to start moving in the right direction again. Those failures also reflect negatively upon the institutions and people responsible for doing the necessary work.

Frankly, it’s hard for me to be very optimistic about the USA’s future. After all, we now live in a country in which one of our current President’s most heavily lithified cronies apparently felt that it’d be a good idea to post a “GOFUNDME” request with a set of crosshairs imposed upon a Federal District Judge’s picture to raise money for his defense in her criminal court. It would be nice to believe that such things couldn’t possibly be happening but they are.

“After fifty-five years as a practicing US scientist238 ‘I’m seeing an increasing rejection of science by my fellow U.S. citizens.’ Climate

238 Most of this paragraph is a comment by “@California Scientist” in response to a New York Times article entitled, “White House Panel Will Study Whether Climate Change Is a National Security Threat. It Includes a Climate Denialist”. Since I couldn’t say it any better, I won’t try:
change is not only real, it is beginning to displace people around the globe and will almost certainly contribute significantly to increasing conflict over loss of habitable land and dwindling resources. Instead of facing this growing crisis we choose to ignore the science, which is seen as a threat by industries including oil companies. Pay attention to what is happening worldwide: insect and animal species and numbers are dropping precipitously, heat waves and severe weather events are increasing, the Arctic and Antarctic are heating and melting much faster than predicted. And how do we respond here in the U.S. We elect a president and administration who do not believe in science. It is hard to be optimistic but we have no choice but to advocate for policies and practices based on our best science, and to hope that, somehow, sanity prevails.’” (@California Scientist 2019)

The good news is that a sizable number of relatively (to me anyway) brilliant young people (Beckers 2016 and the Weinberg http://Foundation.org), several environmental groups, and some especially distinguished senior scientists have also taken up Goeller and Weinberg’s cause (Pro nuclear 2018, Pandora’s promise 2013). In April 2015, nineteen prominent environmental scholars released “An Ecomodernist Manifesto” representing a declaration of principles for new environmentalism. Its summary says: "We offer this statement in the belief that both human prosperity and an ecologically vibrant planet are not only possible, but also inseparable. By committing to the real processes, already underway, that have begun to decouple human well-being from environmental destruction, we believe that such a future

I’ve started it off a bit differently because “@California Scientist” is apparently about a decade younger than I am.
might be achieved. As such, we embrace an optimistic view toward human capacities and the future." (Ecomodernism 2018).

Even better is the fact that many of the young and not-so-young people recently elected to the US Congress realize that the management system they’re become a part of is badly flawed and that “radical” changes akin to those occurring during the Roosevelt administrations are long overdue (WP 2019).

The best news is that there are several especially promising reactor/fuel cycle concepts for the world’s serious NE R&D experts to investigate. If I had a say in such things, I’d recommend that a great deal of attention be paid to developing something along the lines of the unmoderated, two fluid, thorium-fueled MSRs studied by ORNL almost a lifetime ago (Alexander 1959) – the same work that inspired this book’s tube-in-shell reactor concept (Figure 16). The reason for this is that any such reactor would be cheap, compact, modular, extremely powerful, and require so little startup fissile that enough of them could be built to fully electrify the whole world within three or four decades.

In terms of which country is most likely to do the work required to actually implement my scheme, I’d bet upon China. It’s steadily firing up state-of-the-art light water reactors, its new fast reactor went to full power before Christmas (2014), it has begun construction of a new high-temperature gas-cooled nuclear reactor (Chinese HTR) in April (2015) (Forbes 2015). Most importantly, it has also apparently decided to commit 22 billion yuan ($3.3 billion) to developing the molten salt reactor technology that the US abandoned 47 years ago. This effort will no doubt be aided by its recent decision (25 March 2019) to collaborate with France – a move that is likely be welcomed by the folks responsible for developing/studying the MSFR. To help address its need for much cleaner electrical power while its MSRs are being researched, China is
relying upon 27 conventional nuclear reactors plus 29 Generation III+ (solid fuel) LWRs currently under construction. It also intends to build an additional fifty-seven more estimated to generate a total of 150 GW\textsubscript{e} by 2030.

Its chief competitors in the “advanced reactor” business are apt to be Russia and South Korea. Neither have let themselves become dominated (or led) by know-nothings and fear mongers and both build and export affordable nuclear reactors. Russia currently leads in the development of breeding-capable reactors but it is reasonable to expect that when China’s “collectivized” mind has decided how best to go about building them, it’ll quickly overwhelm its competition in that arena as it has in every other it has entered\textsuperscript{239}.

China isn’t apt to be leading that campaign because it has more experience with nuclear power or can operate reactors more efficiently and safely than do we here in the West. It’ll be leading because it’s become extremely rich\textsuperscript{240} and its political leadership demonstrates both the will and foresight required to pursue activities apt to serve their

\textsuperscript{239} India has expressed a great deal of interest in developing a thorium breeder reactor-based, nuclear fuel cycle. However, in my opinion, it is unlikely to overtake France, Russia, South Korea or China. It will however continue to be a good customer of countries able to build affordable nuclear reactors – especially if they can “burn” thorium

\textsuperscript{240} GDP “counts” the movement of money, not its value. With any realistic measure (e.g., “purchasing parity”) of gross national product (GDP), China is already about twice the “size” of the USA. We’re still considered “bigger” because we charge each other more for the services representing \~ 77% of our GDP. APPENDIX XIX goes through some comparisons of public transportation costs between the the USA and foreign countries. Since a nation’s “GDP” is based upon how much its people charge each other for goods & services, China’s cheap train service hurts its standing relative to the USA via that measure of national size/importance/greatness.
county’s best interests over the long haul. China’s political leaders accept the fact that it’s their responsibility to provide a safe, comfortable, and clean world for their descendants – the USA’s don’t. China’s leaders also choose to believe in scientific consensus and that both intra and international cooperation is beneficial\textsuperscript{241} - the USA’s consider climate change to be a hoax & that trade barriers (tariffs) & intellectual property hoarding constitute the best way to deal with foreigners. Consequently since circa 1978 China has been demonstrating that it is possible to incentivize its entrepreneurs to do what’s required to address China’s (and the world’s) “technical” problems without ceding control/choice of those efforts’ ultimate goals. It’s been done by lending state support to targeted industries and technologies, particularly those infrastructure-related activities required to address technical issues like those discussed in this book. We should also remember that China is already heavily involved in African development as a part of its 65-nation “Belt and Road” initiative. The opinion of some Western World politicians that such activity is necessarily “greedy and evil” is wrong-headed. It is a good example of “help-your-neighbor globalization, not colonization, and African agency, not Chinese rapacity” (Bräutigam 2018).

Unfortunately, while this little book’s clean, green, rational and much more egalitarian scenario is likely possible, I don’t consider it to be a certainty because implementation would require that technical-based

\textsuperscript{241}“Competition has been shown to be useful up to a certain point and no further, but cooperation, which is the thing we must strive for today, begins where competition leaves off.” — Franklin D. Roosevelt
reasoning and border-ignoring philanthropy, not “human nature”, determines what actually happens. Collectively, Homo sapiens including the majority of its good team-playing scientists and engineers seem to “think” more like 50 crabs in a gunny sack than do individuals like James Hansen or Albert Einstein. During the next few decades human nature could “trump” rational behavior in China as it has elsewhere. That is the most compelling argument anyone can make to me about why mankind should not pursue a nuclear solution to the future’s otherwise inevitable energy-related social, environmental, and economic issues.

There are many people who fear the effects of overpopulation upon the environment and, consequently, think that other people should be left to starve, or freeze, or die of overwork, or…etc., in order to cut their numbers. Overpopulation remains an issue because the world’s approach to implementing its leadership’s business models severely impacts the natural world while leaving many people poor, ignorant, desperate, miserable and almost perpetually pregnant. These are facts we need to confront, not ignore.

If we want to utter the words “brotherhood”, “equality”, or “compassion” with any semblance of honesty, we must change our business models, the first step of which should be to provide everyone with abundant, cheap, clean, and reliable nuclear energy. If that comes to pass, there won’t be a “population problem”, global warming will abate, the rivers will run free again, and we’ll stop converting the world’s

242 After all, China’s people are still the primary consumers of rhino horns, pangolin parts, bear gall bladders, shark fins, elephant ivory, etc.
remaining truly natural regions into palm oil plantations, cattle feedlots, and soybean farms. Doing so might even bring an end to the Anthropocene’s on-going “Sixth Extinction” (Kolbert 2014).

If we refuse to do such things, or too worried about our economy, or think we should only be obligated to attend to our own needs, or willing to do nothing and thereby sentence other people to death and destitution, then the least we can do is to admit that that’s what we chosen to do – not continue to demonize the technology or people that could address the technical issues responsible for most of humanity’s problems.

In mid-2017, this old but still fairly young-at-heart cynic answered this QUORA question, “Will nuclear power make a major comeback in the near future in the US?“ with,

“I doubt it. The USA has too many cultural barriers in place to do anything that would primarily benefit its own citizens (as opposed to powerful special interests) in the near future (e.g., by 2050). Developing/implementing a nuclear renaissance capable of addressing the consequences of its addiction to fossil fuels will require far more paradigm shifting than our leadership seems capable of.”

I hope that a future generation of US scientists, engineers, and politicians will do whatever’s necessary to prove my QUORA answer wrong. If we become willing to face real threats, overcome unfounded fears, perform the necessary research and then act upon those findings, we could address the future’s challenges and leave our descendants with a safer, happier, more equitable, and much less negatively human-impacted world than the one we’re living in. Doing so would obviate the otherwise likely possibility that they will be struggling to survive in a Malthusian dystopia.
Chapter 12. Homework problems

(Their/my goal is to encourage students to learn how to put concepts, suggestions, and numbers into proper perspective)

MISC. DATA/RELATIONSHIPS (also see GOOGLE, Engineer’s toolbox, WIKIPEDIA and this book’s Table 1): one US pound = 454 grams; 1 calorie heat energy raises the temperature of one gram water by one centigrade degree; one centigrade or kelvin degree = 9/5 Fahrenheit (F) degree; water freezes at zero degrees Centigrade or 32 degrees F; one BTU = heat required to heat/cool one pound of water by one Fahrenheit degree; one calorie = 4.18 J; one kilocalorie (kcal) = 1000 calories (the “calorie” unit usually quoted for foods etc. are really kilocalories; e.g., one gram fat = 9 kcal, 1 gram protein or carbohydrate (starch or sugar) ≈ 4 kcal, one gram petroleum (oil) ≈ 10 kcal); heat capacity of water = one calorie per centigrade degree per gram; burning one pound of lignite coal generates 6500 BTU worth of heat (it’s about one half as “energetic” as is pure elemental carbon or anthracite coal); one gram mole of fissile uranium (235U) weighs 235 grams and contains an Avogadro’s number of atoms; i.e., 6.023E+23; fission of one actinide atom generates 3.2E-11 J of heat; 1 US ton = 0.908 metric tonne (1 tonne = 10^6 grams = 1000 kg); 1 mile^2 = 640 acres = 1609^2 m^2; 1000^2 m^2 = 1 km^2 = 100 ha.

Miscellaneous

1. List the USA’s “Military Advisory Board’s” key findings circa 2014 re the consequences of anthropogenic carbon dumping. What’s the rank (O?) of the lowest ranking member of that board?
2. If peanut butter has 6 kcal/g and “white” bread 4kcal/g, a slice of bread weighs 20 grams, and the same amount of each constitutes a peanut butter sandwich, how many such sandwiches would it take to feed someone for a year? (Use the same daily calorie-need figure I’ve assumed for the future’s Africans)

3. How many grams of protein would he/she be getting per day? (GOOGLE the necessary food composition numbers)

4. Is my book’s estimate of Mankind’s total raw energy requirements (~570 EJ/a) still valid? (I started writing it several years ago)

5. How many barrel of oil equivalents (BOEs) does one peanut butter sandwich represent? How many kWh is that? How many horsepower hours?

6. One peanut sandwich per minute = how many watts? (ans =13.9 kW)

7. If 1/x + 23/x^2 = 3/x^3 what’s X to two significant figures? (ans =0.13) hint: set up an EXCEL spread sheet that calculates each side of the equation based upon an input in another box and then ratios the two results … keep inputting different x’s until that ratio is 1.00 +/- 0.01.

8. What would x be if 1/x + 23/x^2 = 3/x^3 + 283/x^4?

9. Assuming that electricity costs 6 cents/kWh and desalination’s energy requirement is 3 kWh/m^3, what would the power required to irrigate one US acre with 30 inches of water cost? (show your work, ans =$555)

10. repeat for 20 inches of water per ha

11. how many calories equals one BTU? (show your work – ans. 252)
12. What’s lignite’s heat of combustion in units of joules per gram?

13. How many metric tonnes of lignite coal must be burned to heat 1,000,000 (1E+6) gallons of water (1 gal=3785 grams) from 70F to 120 F? (ans = 29.1)

14. How much fissile uranium (metric tonnes) must be fissioned to do the same thing? (ans = 5.37E-6 tonnes)

15. If only the 235U in natural U (NU) actually fissions, and it represents 0.7% of natural uranium, how much natural uranium must be used to heat 1E+6 gallons of water (1 gal=3785 grams) from 70F to 120 F?

16. If lignite coal costs $25 per metric ton, what’s heating that much water with it going to cost?

17. If natural uranium (NU) costs $40 per kg, 5/7 of its fissile ends up in LWR fuel & fuel represents 15% of total LWR power cost, what’s heating that pool with electricity generated by a CR =0 (no breeding), 35% heat-to-electricity power plant going to cost? (ans = $282)

**OIL SHALE**

According to WIKIPEDIA the world’s shale deposits are supposed to contain 6.05 trillion 42 US gallon barrels (962 billion cubic meters) of shale oil, with the largest resource within the United States accounting for ~80% of it

18. If the USA’s shale deposits average 100 meters thick, possess a density of 2.5 g/cc, and contain an average of 40 liters of 0.9 gram/cc “oil” per metric tonne, what’s the land surface area of the USA’s share of those deposits? (show your work)

19. How many Utah’s (area ~ 89,000mi² would that be?) (ans = 0.334)
20. If “advanced” technologies could retrieve 50% of that oil, how many tonnes of such shale must be processed to “power the future” (i.e., generate 22.4 TWe) for ten years using 50% thermal-to-electricity-efficient oil-fired power plants? Assume an oil density of 0.9 g.cc.
\[ \text{ans} = 7.49 \times 10^{11} \text{ m}^3 \]

21. If those shale deposits are 50 meters thick, how many km\(^2\) of land must be “disturbed” to accomplish that? (ans \(1.50 \times 10^4\))

22. If the average depth (to their tops) of those deposits is 500 meters & the density of their overburden is 3.0 g/cc, how many “RMS Titanics” (\(\sim 47,000\) tonne displacement) worth of such rock must be removed each year to get to that fuel resource? (ans = 478 million)

**US uranium/thorium resources**

Assuming
- that the USA has a total of 5 Utah’s worth of phosphate & “black” shale rock deposits
- they average 200 ppm by weight total fertile actinides
- a total shale rock actinide accessing/processing cost of 50 dollars per tonne,

23. How long (years) could a breeder-based, 50% thermal to elec. nuclear fuel cycle provide 22.4 TWs worth of useful energy (electricity) /year burning them as fuel? (ans = 2.01 million years)

24. How much would that actinide fuel cost per KWh? (ans = 1.1E-5 dollar)
25. What would its power cost customers per kWh if the reactors’ up-front cost is one billion/GWe, their maintenance cost/GWe is 20 $million per year/GWe and their lifetime 50 years?  (ans =0.46 cents/kWh)

WIND POWER
The general rule-of-thumb for wind farm spacing is that turbines should be no closer than 7 rotor diameters away from each other. Taking the little figure depicted below into account and assuming that a 2 MW rated windmill’s blades sweep a 90 meter, let’s determine out how many of them could be sited within a square 100 km on a side.
We’ll start out by deriving the relationship between the total space (area) between circles in a close-packed array and that of the circles themselves. (see https://en.wikipedia.org/wiki/Trigonometry)

26. In an infinite array of such close-packed circles how many spaces would there be relative to circles (hint: to help visualization, extend the figure above to at least, 4 layers of 4 circle rows , ans =1:1)

27. What is the area of the triangle depicted in fig 1 in terms of circle radius, r? (hint: One half its height times its width =?)

28. What is the area subtended by 60° of a complete (360°) circle with radius r? Ditto for a 30 degree slice of that circle? (ans 30/360*pi*r²)

(between-circle space would be twice the difference in Fig 1's triangle's area and that of the two circles touching each other within that triangle)

29. What's that in terms of r? (ans =2*(Cos 30°*r-(30+60)/360*pi*r2))
30. If \( r = 1 \), what’s that number?

31. What’s the area of the circle plus its accompanying space relative to the circle’s area?

32. And now, finally, how many properly spaced 2 MW turbines could be packed into our 100km/side square? \( \text{(ans = } \sim 30,600) \)

33. If their average capacity factor were 0.3 how many average watts could that humungous wind farm supply?

35. Assuming that that average amount of wind-generated energy were enough to meet energy demand but that power demand is invariant (a 24/7 demand that couldn’t be “load shed”) how much back up storage battery capacity (kWh) would the system need if wind could be relied upon to recharge the batteries some time each day? \( \text{(ans. } 3.08E+08 \text{ kWh}) \)

36. If its batteries cost one half as much as do TESLA’s Power walls ($7000/13.5 kWh), what would that system’s batteries purchase cost be?

37. If those windmills cost $1/watt (nameplate capacity) to build/maintain & last for 20 years, what would the power generated by them cost ($/kWh)? \( \text{(ans } $0.019) \)

38. If their backup batteries last an average of ten years, what would they add to the electricity’s cost? \( \text{(ans } $0.046/kWh) \)

39 Assuming 10% profit, what would such power cost a retail customer per kWh?

\( \text{(this figure underestimates a genuinely practical system’s cost because wind’s unreliability would require more back up capacity –batteries, etc. and/or power shipped in from other regions)} \)
HOME HEATING ENERGIES

The insulation value of materials is inversely proportional to their thermal conductivity "k" or lambda-value (lowercase $\lambda$): the lower the $k$-value, the better it is for insulation. Expanded polystyrene (EPS) has a $k$-value of around 0.033 W/mΔT [k or°C], phenolic foam insulation's $k$ is around 0.018, wood's from 0.15 to 0.75, and steel's about 50.

Assuming the following:

- a year-round outside temp of 0°C and inside home temperature of 20°C
- your home has a 4' by 8' (2.97m$^2$) “picture window” situated where 50% of "maximum possible" sunlight (1000watts/m$^2$) gets through it for an average of 6 hours day
- 100% of such sunlight is degraded to heat energy within your home

40. How many Joules worth of such “useful” solar heat is-generated for you per day?

41. How many kWh is that? (ans =8.91)

42. If that window were to consist of two, clear, uncoated glass panes with air between them possessing an overall “R”-value of 0.35 ΔTm$^2$/W (R =.35= ΔT* m$^2$/W), how much of your home's heat (Joules) would be lost per day?. (pay attention to the R value’s units) (ans =1.47E+7 J)

43. If an inside "shutter" consisting of a 2.97 m$^2$ slab of 5 cm thick phenolic foam board (were to cover that window when the sun wasn't striking it, what would that window's daily net heat input to your home be per day? (Joules) ans=2.83E+07 J
44. Next, assuming that you are 30 years old, actually own our home & really want to stay there, possess a secure but only $10/hr-after taxes job, electricity costs you 9 cents/kWh, and the above-mentioned insulation board costs $50/4’by 8’ sheet, would you consider making such a window shutter?

45. If you really "owned" only 10% of that home or were renting & your job consists of $15/hr gigs interspersed with long & random periods of unemployment, would you consider making such a shutter?

46. If that window were to be replaced with a section of fairly well-insulated (e.g. with a 15 cm thick layer of EPS) wall and 2.97m² of state of the art (19% efficient) solar panels, how much heat energy could those panels supply your home via a baseboard (resistive)-type heater? (ans= 6.09E+06 J)

47. How much heat could those solar panels supply you if that ~$50 baseboard heater were to be replaced with a $1000 heat pump possessing a Coefficient of Performance (COP - look it up) of 3? ans= 1.83E+07 J

**REACTOR NITTY GRITTY**

48. GOOGLE up the densities of "natural" NaCl and UCl₃ at room temperature(25°C) and use them to estimate the density of a 65 mole % (i.e., 6.7 moles NaCl to every 3.5 moles UCl₃) molten salt at 650°C assuming that the stuff expands 150 ppm volume-wise per degree. (ans =3.34 g/cc)

49. Assuming an enrichment level of 20%, how many fissile atoms would be in one cc of that liquid salt mix? ans = 9.73E+20 atoms ²³⁵U/cc)
50. If the reactor containing it has a "core tank" consisting of a sphere 1.8 meters in diameter, how much of that fissile (tonnes) would be in it?

51. If that tank's walls were one quarter inch thick titanium what would it weigh?

52. Assuming that's it's made of CP grade titanium (currently~$17/kg) & that cutting/welding it would double that figure what would a replacement core tank cost? ans $9,900

53. If that reactor were to generate 2 GW's worth of heat & its heat exchangers' size-to-heat-exchanger capacity ratio were the same as the MSFR's (GOOGLE Carlo Fiorina's PhD thesis) how much additional fissile would be required (tonnes)? ans =1.16 tonnes

Liquid metal fast breeder related exercises

ref. EBR II description: https://inldigitallibrary.inl.gov/Reports/ANL-0001.pdf

To a first approximation let's assume that our reactors has a right circular cylindrical core 73.4” in diameter and 71 inches high

it’s broken up into 637 close packed hexagonal “assembly spaces” each of which can contain either a “driver fuel”, blanket fuel, inert neutron reflector rods(e.g. contains stainless steel rods), or shielding, e.g. lead rods) assembly

liquid sodium pumped upwards throughout that core's interstices carries off the heat

sixty HEU (high enriched uranium) driver fuel assemblies at its center are surrounded by 67 mixed HEU plus (DU or NU) assemblies which, in turn, are surrounded by pure fertile (only NU or DU) containing blanket assemblies

Each assembly consists of a thin-walled, 2.29” flat-to-flat diameter, hexagonal 304 stainless steel “can containing 91 metallic “pins”

each fuel rod consists of a 91 inch long, thin-walled (0.012”) steel tube containing spacers, liquid sodium (aids heat transfer), and a uranium fuel pin - the 0.01” space
between the fuel pin and the tubing’s wall contains (liquid) sodium which enhances heat transfer & permits the fuel “meat’s” expansion – the purpose of the spacers is to keep the uranium pin at the center of the much longer fuel tube/rod. In practice each tube/rod is wrapped with fine wire to prevent them from touching each other within the hexagonal can.

Each U-bearing fuel pin is 0.13” in diameter, 13.5 “ long, and consists of a 10% Zr by weight alloy of zirconium (density=6.49 g/cc) with uranium (19.1 g/cc).

54. What's this reactor’s core region’s total area (cm²)? Ans = 2.73E+4 cm²

55. What's an assembly's cross sectional area, ans =
2.29²/(2cos30)+2.29(1+1/(2cos30))*2.542 = 42.86cm² (figure out for yourself how this equation/answer was obtained – a sketch will help you visualize it)

56. Assuming that the 60 innermost assemblies contain HEU driver fuel, what's the diameter of that "hottest" region of the reactor’s core? ans = 59.7 cm

57. What's the volume of that region (cc)?

58. What's the density of its 10% Zr/90% fuel "meat"? Ans =15.99 g/cc (hint add partial molar volumes)

59. What’s the mass of each fuel pin (grams)?

60. What's the total amount of fissile(²³⁵U) in this little reactor’s core region (grams)? ans 14.6 kg

61. How many fissile atoms/cc are in that region? ans =1.65E+21 atoms/cc

62. assuming that the surrounding out-to-the edge "blanket" assemblies had fuel rod tubes containing 1 meter (not13.5”) long DU "pins" in them, how much uranium would they contain? ans 13.15 g.
63. Assuming that those blanket assemblies were replaced with stainless steel “reflector” assemblies (no breeding possible) & the reactor could burn 20% of its fissile before FP buildup brings everything to a halt, how long could it run while producing 60 MWt? (ans =46 Days)

64. Assuming the same power generation per unit volume as the little test reactor’s innermost core region, how big would a 45% efficient thermal to electricity efficient 1 GWe commercial reactor’s core have to be? (cubic meters)

65. If it’s a right circular cylinder with diameter = height, what is its size?

66. How many such driver fuel pins would be in that reactor's “hot” region? ans = 42,700

67. If that reactor's solid-fueled hot core region were to be replaced with a same sized/shaped MSR core tank filled with the UCL$_3$/NaCl salt mix described in problem 48, what would that salt’s uranium's enrichment level have to be to exhibit the same fissile atom/cc concentration (650 C?) ans = 8.53% $^{235}$U

**Ocean acidification exercises**

The mass of the Earth's atmosphere is about 5.1480×10$^18$ kg and its mean molecular weight is about 29 grams/mole (mostly O$_2$ (32 g/mole) & N$_2$ (28 g/mole) & about mole 1% total other gases)

68. If mankind were to continue to generate 85% of ~580 EJ/a by burning pure carbon (very much like anthracite coal, ~ 33 MJ/kg heating value) for the next 30 years how much CO$_2$ would be generated? (ans = 1.64E+15 kg)

69. At 44 g/mole how many moles of CO2 is that?
70. How many moles of gas does the Earth’s atmosphere contain?

71. At today’s ~410 ppm by volume atmospheric CO$_2$ conc. How many moles of CO$_2$ is already in it?

72. How much lower will burning that “coal” push the pH of the oceans’ surface waters (calculate pH of its water for both partial pressures)

    and finally …

73. How much wood could a woodchuck chuck if a woodchuck could chuck wood?

ACKNOWLEDGMENTS

I’d like to begin by thanking the three people whom I’ve come to regard as my retirement hobby’s topmost heros; Hyman Rickover, James Hansen, and Alvin Weinberg. Next, I’d like to thank Kirk Sorensen whose “Energy from Thorium” blog/discussion forum greatly simplified my learning of the hows, whys, and results of ORNL’s molten salt reactor research. Among the other similarly-motivated people that I’ve come to respect since then, several really stand out: Robert Hargraves, Ripu Malhotra, Lars Jorgenson, David LeBlanc, Ian Scott, Ed Pheil, Professor Barry Brook, Alex Cannara, Professor Ken Caldiera, Carlo Fiorina, Manuel Aufiero, Professor Per Peterson, Professor Charles Forsberg, Professor Roger Pielke, Professor Nickolas Tesoulfanidis, David Holcombe, Richard Rhodes, Mathijs Beckers, George Erickson, and Professor Tom Dolan. I’d also like to give a shout-out to Eric Loewen, currently GE Hitachi’s chief consulting engineer, for being the
best “boss” I ever had at INL. Finally, I’d like to thank Professor Rattan Lal for giving me my first opportunity to explain how the agricultural sector could provide some of a nuclear renaissance’s most compelling “killer apps.”

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Chapter 13. APPENDICES

Appendix I Reprocessing

Nuclear reactors like automobiles must consume fuel to do useful work. When fossil fuels (typically gasoline, diesel oil, or propane) are burned to power an engine, they are consumed both immediately and almost completely. When that fuel is gone, energy production totally stops. Nuclear reactors are usually incapable of achieving such near complete burn-up because as their fuel (usually fissile uranium) is burned via nuclear fission, a variety of other elements – fission products (FP) – are created and become intimately associated with the remaining fissile. Because they absorb the neutrons that energize fission, such FP accumulations eventually poison the system and stop the reactor. Some fission products may also damage the structural integrity of solid-type fuel assemblies. Even though a good deal of fissile material may remain in such fuels, it can’t be burned until separated from neutron-absorbing fission products and possibly compromised cladding via some form of “reprocessing”.

Conventional reprocessing

Let’s look into the history of the nuclear fuel reprocessing facility about which most of this book’s examples were derived.

The USA’s Atomic Energy Act of 1946 established the civilian Atomic Energy Commission (AEC) to direct atomic energy “toward improving the public welfare, increasing the standard of living, strengthening free competition among private enterprises so far as practicable, and cementing world peace.” That Act required the AEC to conduct research in nuclear energy “through its own facilities….” Consequently, in 1949, following a nation-wide search, the AEC established the NRTS in
southeastern Idaho, its first field test facility and only dedicated reactor proving ground. That area was chosen because of its isolation, climate, favorable geology, abundant subsurface water, and social-economic factors including local government support, existing infrastructure, and ready availability of manpower, land, and construction materials. The NRTS originally covered 177,000 acres but eventually expanded to cover 569,000 acres (890 square miles) of Idaho’s “high desert” in the northeastern end of its Snake River Plain. The Site’s name was changed three times, in 1974 to the Idaho National Engineering Laboratory (INEL), again in 1997 to the Idaho National Engineering and Environmental Laboratory (INEEL), and finally to the Idaho National Laboratory (INL) in 2005. Its original mission was to provide a suitably remote (safe) area where nuclear energy research, development, and testing could be conducted with minimal impact to the public. Initially the AEC planned to construct only five reactors there over a ten-year period. However, rapidly expanding technologies and a nationwide sense of optimism (as opposed to today’s pessimism) that saw no limits to the potential of nuclear energy greatly extended its mission. Eventually, fifty-two, mostly first-of-a-kind, reactors were constructed at the NRTS including Rickover’s first pressurized water submarine reactor (PWR) and Untermeyer’s boiling water reactor (BWR) which between them came to dominate civilian nuclear power worldwide. The
NRTS’s experimentation regarding reactor safety, design, and applications influenced virtually every other reactor in the world. The first four facilities circa 1950 included the Experimental Breeder Reactor I (EBR-I), the Naval Reactor Facility (NRF), the Materials Test Reactor (MTR), and the Idaho Chemical (re)Processing Plant (ICPP).

Succeeding expansion included several additional centers each reflecting a new direction in nuclear research or filling necessary operational functions. From the beginning, political tides and changing world events periodically shifted priorities. Although those influences varied, they fell into two categories: national defense and peaceful applications.

Throughout history, almost all government facilities everywhere have bent to the needs of national defense at one time or another. Conceived as it was in the aftermath of World War II, the initial throes of the Korean War, and the heightening tensions which defined the Cold War, the NRTS exhibited both extremes. For example, its Naval Reactors Facility, devoted itself entirely to projects related to national defense, the most prominent of which was development of the reactors that power most of the U.S. Navy’s submarines and aircraft carriers. Other NRTS facilities contributed to that cause less directly. For example, the ICPP’s construction schedules were given a boost when shortages of uranium and plutonium threatened to compromise weapons production at other AEC labs. Consequently, the first batch of uranium recovered/recycled by it came from the Hanford Site’s plutonium production reactors.

However, not many of its subsequent fuel reprocessing runs had to do with weapons production or even national defense. President Eisenhower’s “Atoms for Peace” program encouraged the development of peaceful uses for nuclear energy (electricity generation, medical applications, food irradiation/preservation, etc.) and much of the subsequent work done at the NRTS was directed toward furthering those
efforts. One of the most pressing questions at that time was how the materials and components (e.g., fuel assemblies, fuel cladding, and reactor construction materials) in civilian power reactors would perform under intense irradiation. That why the Material Test reactor (MTR), a high flux, water thermalized neutron reactor, was designed to determine, how well the materials being considered for use in those reactors would withstand several years of exposure. This testing was accomplished by bombarding materials (“coupons”) with thermalized neutrons. Since the MTR was a very “hot” reactor enough fission products built up within its aluminum-clad highly enriched (bomb grade) uranium fuel assemblies to bring everything to a halt every 17 days or so. Its so-depleted fuel assemblies then had to be removed and replaced with fresh ones. Less than 30% of the original $^{235}\text{U}$ in such “spent” fuel was burned per cycle which means that it had to be recovered for recycle. The NRTS’s reprocessing facility, Idaho Chemical Processing Plant (ICPP aka “Chem Plant”) was designed to be the MTR’s support facility and fulfilled that mission for nearly four decades, recovering millions of dollars worth of fissile ($^{235}\text{U}$) that was fabricated into new fuel elements for both it and the Site’s other test reactors.
The NRTS’s Chem Plant was far more versatile than were those of the federal government’s “production” (of bomb grade plutonium and tritium) facilities (primarily Savannah River and Hanford) It could recover the uranium within fuel assemblies clad with virtually any sort of material – aluminum, stainless steel, zirconium, graphite or ceramic composites.  

It also did a better job of managing its reprocessing wastes in that, rather than simply neutralize the acid in them and store the resulting mixture of oxy/hydroxyl sludges plus salt saturated liquids in tanks, about 90% of it was calcined and the resulting more stable/innocuous sand-like dry powder stored in stainless steel/concrete “binsets”.

Throughout the years, the Chem Plant recovered both uranium and certain valuable fission products from nearly one hundred different research and power reactors throughout the nation. By the end of the 1970’s most of the DOE’s test reactors had been shut down
(“decommissioned”) so it was reconfigured/repurposed so that it could, in principal at least, recover the highly enriched uranium remaining in spent Naval reactor fuel assemblies.

That’s where things went awry. Although nominally zirconium-clad, the Navy’s LWR fuel assemblies were apparently overplated (alloyed?) with the secret element mentioned in footnote 121 and APPENDIX that probably rendered their dissolution more difficult than assumed by the new facility’s designers (See APPENDICES XVI & XVIII). That plus actions taken to address hyperconservative safety concerns (see APPENDIX XVI) rendered its productivity so poor that the Navy’s decision makers eventually decided to cut their losses and just continue to “temporarily” store its spent fuel).

The technical issues leading to that decision included…

• The design of that facility’s three individual dissolvers didn’t render it impossible for an accumulation of undissolved HEU fuel particles within them to randomly assemble themselves in a “critical” configuration (they weren’t geometrically safe & the uranium in question is/was highly enriched; i.e., “weapons grade”). That fact also dictated addition of a neutron poison (cadmium nitrate) to the dissolvent (HF) which tended to plate-out metallic cadmium upon the fuel assemblies & thereby inhibit their dissolution.

• Also, in order to lower initial build costs the product solutions generated by all three dissolvers were to be sequentially fed to a single “accountability” tank which meant that the batch-wise fuel dissolution process performed in each had to be synched 120 degrees out of phase time-wise with the other two dissolvers

• Fuel assembly dissolution rates were unexpectedly low and erratic (probably at least partially due both to the mysterious element within
them about which no one could speak and, perhaps, a different fuel configuration - plates instead of tubes?

Those technical issues combined with the fact that any sort of “criticality incident” would immediately shut the entire facility down for at least a few months (& maybe permanently) meant that it had to be operated in an extremely “conservative” fashion; i.e., every few dissolutions had to be followed with an aggressive “heel out” (the addition of more dissolvent followed by another dissolution period followed by another round of product solution characterization) to reassure everyone that everything had indeed been dissolved before another fuel assembly could be processed.

This plus the fact that the process modifications required to achieve satisfactory productivity caused the dissolvers to corrode more rapidly than expected meant that DOE/INEL then had to go back and ask for another half $billion or so to replace them. That proposal was rejected. (APPENDIX XVI is an “insider”’s description of what happened.)

The State of Idaho objected to that facility’s shutdown, demanding that the DOE develop a plan for managing both the Navy’s spent fuel and all of the already-generated reprocessing wastes, both liquid and solid, plus various other wastes scattered across the rest of the INEL. A lawsuit to prevent any further receipt or storage of spent fuel until such a study had been completed accompanied that demand. In 1995 this conflict resulted in an agreement (the “Batt Agreement”) between DOE, the State of Idaho, and the U. S. Navy outlining the future of fuel storage and waste management at the INEL. DOE promised to “clean up” everything at the Chem Plant including the roughly one million gallons of still-liquid reprocessing wastes within several of its then >40 year old tanks. In 1998, DOE identified the Chem Plant’s Main Processing Building (CPP-601) for removal, along with its Fuel Storage Building (CPP-603), and
several support structures. In 2005, DOE deemed most the remaining ICPP structures including its waste calcination facility (NWCF) obsolete and the deactivation, decommissioning, and demolition (DD&D) of its buildings and other structures began, including everything associated with fuel reprocessing.

This left the folks who had worked there without much to do other than watch DOE’s new subcontractors tear down its buildings, bulldoze everything into pits and pour gravel and/or concrete over it. The exceptions were the folks given an opportunity to try to get INL’s now infamous “steam reformer” (IWTU) up and running. As of this date (March 2019) they’ve spent 14 years and about a billion dollars trying and haven’t succeeded yet.

Anyway, the INL’s Chem Plant was built to do what virtually every other fuel processing plants does; i.e.,

1. Receive and store spent fuel until it’s “cooled off” enough to work with – typically at least one and more often, ~five years

2. Dissolve that fuel in a way that eventually generates an acidic aqueous solution containing several molar nitrate ion. However, unlike most civilian fuel reprocessing facilities, the Chem Plant dissolved cladding along with the fuel “meat” thereby generating solutions containing whatever the cladding consisted of along with the uranium, plutonium, and fission products.

3. Extract the uranium and plutonium from that solution via countercurrent liquid-liquid extraction with ~30% tri-butyl phosphate in a kerosene-like organic solvent. (uranium/plutonium are extracted as zero-charge nitrate-based, “ion pairs”, e.g. $\text{UO}_2^{4+}(\text{NO}_3^-)_2$. This is a key step of the “PUREX” process)
4. Transfer the U/Pu in that solvent to a second aqueous phase by contacting it with water containing very little nitrate (e.g., 0.1 M HNO$_3$ which breaks up the ion pair rendering the U/Pu insoluble in the organic phase).

5. Boil off most of the water in that solution to concentrate it, add aluminum nitrate to bring the nitrate concentration up again, add some hydroxylamine and/or ferrous sulfamate to reduce/convert quadrivalent Pu to unextractible trivalent Pu, and then extract the uranium from it, again as an ion pair, via countercurrent liquid-liquid extraction with/into “hexone” (methyl isobutyl ketone). This “2nd cycle” hexone/aluminum nitrate-based process is called the “REDOX process“.

6. That hexone phase was first rinsed with more aluminum nitrate to remove contaminants and then contacted with dilute nitric acid to transfer the uranium back into another aqueous solution.

7. To generate an even purer uranium product, steps 5 and 6 were generally repeated (this was the Chem Plant’s “third cycle” extraction)

8. Most of the water in that now very pure uranium nitrate solution was then boiled off after which it was then squirited into a small fluidized bed “denitrator” which converted it to a compact, easily handled, dry UO$_3$ powder ready for shipment off to a customer (usually a fuel fabrication facility).

The wastes generated by such reprocessing consisted of:

- First cycle raffinate (aka “high level waste”): the aqueous phase coming out of the first cycle PUREX extraction. It contains the majority of the fuel’s fission products and cladding components (e.g., dissolved steel or aluminum or zirconium) along with whatever else was added to
either enhance extraction or stabilize the solution (often aluminum and/or calcium nitrate salts).

- Second and third cycle raffinates: these solutions contain lesser levels of fission products, almost all of the plutonium (generally), plus lots of aluminum nitrate.

- Miscellaneous clean up wastes: solutions of sodium (or potassium) carbonate, permanganate, and/or sodium hydroxide were used for cleanup activities throughout the plant primarily because “caustic” readily dissolves the silicic acid gels that gummed up pipes and extraction equipment. Once so-dirtied, they usually ended up in the “sodium bearing waste” tanks along with other small volume miscellaneous waste streams. A good deal of the mercury utilized as a catalyst during the dissolution of aluminum clad fuel elements also ended up in them.

The PUREX process utilized by most of the world’s fuel reprocessing plants entails…

- chopping spent fuel rods into short pieces
- rolling/crushing them to break up/remove their brittle uranium (mostly) oxide pellet contents from their zirconium (usually) tubing “hulls”

---

244 The silicic acid originated from the “purified” ~20 ppm silica ground water utilized to make solutions. The chem plant’s water purification process, dual bed ion exchange, didn’t remove silica very well because it is largely present in ground water as non-ionic silicic acid. Currently, that silica comprises the bulk of the sludges underlying the liquid in INL’s SBW tanks. If INL ever does get its steam reformer going, the current plan is to leave that sludge there along with a hefty fraction of that waste’s total radionuclides, esp. $^{137}$Cs & Pu. (those tanks are are to be pumped until “suction is lost”, not until they are empty).
dissolving that ceramic in strong nitric acid
extracting actinides (mostly U+Pu) from that solution via counter current liquid-liquid extraction with TBP/kerosene
back extracting them into dilute nitric acid
separating U from the Pu by adding a reductant (typ. hydroxylamine or ferrous iron) and more strong nitric acid, and extracting again with more TBP/kerosene - the uranium is re-extracted but Pu$^{+3}$ isn't.

Excellent discussions of just about every aspect of LWR fuel reprocessing can be found in the”best” (second edition) version of Benedict, Pigford, and Levy’s monumental “Nuclear Chemical Engineering” textbook (Benedict 1981). The best description of today’s reactor fuels I’ve found yet is a set of slides generated by Vanderbilt University ‘s Prof. Allen Croft (Croft 2008)

http://www.cresp.org/NuclearChemCourse/presentations/06_CROFF_Presentation.pdf

Future reprocessing
Because there are so many different ways that a sustainable nuclear renaissance might be implemented, I’m just going to describe a few scenarios.

To begin with, rumor has it that DOE/INL is again considering the reprocessing of the Navy’s spent reactor fuels to generate the fissile required by its currently hypothesized multiple small modular and micro reactors all of which are slated to use 19.75% $^{235}\text{U}$ enriched fuel (see APPENDIX XVIII for a discussion of what Naval fuel may consist of). However, this time around, that process would be quite different in that
the fuel’s zirconium cladding etc., would be separated from the remaining uranium oxide plus fission products via “chlorine volatility” (reacting Zr with hot HCl generates gaseous ZrCl$_4$) before the latter is dissolved in nitric acid. Doing it that way would simplify U recovery/extraction, greatly reduce the amount of waste generated, and then render its treatment/disposal much easier/cheaper.

For instance, a way to convert spent LWR fuel to something compatible with a MCFR would be to chop the fuel tubes into short sections, roll/crush them to break up/separate the uranium oxide pellets; powder them; add one mole of ZrCl$_4$ per mole of total actinide; disperse both in 2 moles molten NaCl/mole actinide; and then slowly add zirconium powder while stirring. Thermodynamic calculations indicate that this should produce a fuel salt containing trivalent fissile/fertile actinides in the right amount of NaCl for the mixture to exhibit a melting point < 550°C along with solid filterable/removable ZrO$_2$. The same sorts of calculations indicate that another way to do it would be to disperse finely ground UO$_2$ fuel pellets in molten NaCl and bubble carbon tetrachloride through it. The UCl$_4$ in the resulting PuCl$_3$/UCl$_4$/NaCl solution could then be reduced to UC$_3$ by stirring in one third as much powdered uranium metal.

Converting the same spent LWR fuel to something capable of starting a MSFR or tube-in-shell thorium breeder could probably be best accomplished via the same Purex based process I’ve outlined above. However, a great deal of money has recently been spent demonstrating that it could be accomplished via electrometallurgical “pyroprocessing” (Till 2013). That process invokes electrochemical reduction of such fuel’s oxide-form actinides (uranium along with some TRU most of which is plutonium) to metals after which the uranium and plutonium
are separated via another electrochemical dissolution/redeposition process utilizing different electrodes. In this writer’s opinion that approach is unlikely to be the “best” way to recover any such potentially useful plutonium fissile (the bulk of the so-recovered uranium would be stored for use after the reactor had been started). Pyrometallurgical processing’s chief virtues are: 1) it could be performed upon “hotter” (not so much cooled-off) spent fuel than could any process utilizing radiation-labile water/organic extractants; and 2), it doesn’t do a sufficiently good job of separating plutonium from uranium (or anything else) to generate something that imaginary terrorists could easily make a bomb “pit” out of (it’d be too “hot” to work with or sneak past inspectors).

It would be more reasonable to fluorinate such spent fuel to volatilize the uranium along with some of the FP products and then subject the residue to a PUREX-type separation to recover fissile plutonium. That could be done by boiling that residue in concentrated nitric acid to remove fluorine, diluting that solution with water to generate another one that TBP could extract the Pu from while leaving most of the FP behind.

However, once such fuel has been made and partially “burned” in some sort of MSFR, electrometallurgical pyroprocessing might become a reasonable way of keeping it clean enough to remain useful\textsuperscript{245}. See

\textsuperscript{245} Only 60-70\% of the FP so formed would remain in any MSR’s fuel salt because gasses (e.g., xenon, krypton, and tritium) and elemental metal “scum” formed from FP “noble” at its buffered/controlled redox state (e.g., Ag, Ru, Pd, Pt, Tc, Rh, Re, Sb, etc.) would be continuously sparged/skimmed out of it. Riley et al have recently reviewed molten salt reactor waste and effluent management strategies (Riley 2019).
Delpeche 2008 & Lucotte 2013 for descriptions of some of the salt cleanup schemes being evaluated for the MSFR.

Figure 28  Generic MSFR fuel salt treatment scheme (Lucotte 2013)

The tube-in-shell reactor’s fuel salt could be purified by first fluorinating the $^{233}\text{U}$ out of it (as UF$_6$ gas) and then distilling/collecting the FLiBe off the bulk of the FP under partial vacuum (Smith 1969).
Appendix II  MSFR Isobreeder Fuel Salt Reprocessing

EVOL’s neutronics modeling indicates that the 1.5 GWe MSFR could run at steady state (CR just over 1.0) with just 6 liters per day of fuel salt reprocessing (cleanup)\(^{246}\).

The principle of “additive fractional molar volumes” (see APPENDIX IV) indicates that a fuel salt containing roughly 77.5 mole\%, LiF and 22.5\% of a mixture of (HM)\(F_3\) and (HM)\(F_4\). (HM = sum of actinide (heavy metal) nuclides), would have a density of \(~4.28\ g/cc\) and contain 47.9 moles/liter lithium plus HN fluoride salts.

Consequently, 6 liters of it would contain \(~14\ (0.93*6*0.225*232*47.9/1000)\) kg of thorium\(^{247}\) and 1.59 kg (0.775*7*47.9/1000) kg of \(^{7}\text{Li}\)

Reprocessing (fuel salt cleanup) would involve sparging the fissile \(^{233}\text{U}\) out of the spent salt (as UF\(_6\), another gas) with elemental fluorine (or possibly NF\(_3\)) which would oxidize its uranium to gaseous UF\(_6\). That uranium would then be returned along with \(~14\) kg of fresh thorium and 1.59 kg of fresh \(^{7}\text{Li}\) (both as their fluoride salts) back to the reactor’s fuel salt stream by reducing it back to UF\(_4\) with hydrogen gas.

The spent fuel salt from which its fissile is recovered/recycled could simply be discarded – at least temporarily – because there’s nothing in it

\(^{246}\) The “reprocessing” referred to herein deals with “salt seeking”“fission products, primarily alkalies, alkaline earths, and rare earths, not to what’s continuously done to remove intrinsically insoluble fission products - a total of \(~1\) kg/day/GWe mixture of gasses and noble metal sludge – from the fuel.

\(^{247}\) At steady state about 93\% of the HM in this system’s core would be thorium; most of the rest would be quadrivalent uranium.
that’s really worth the cost of recovery. If it is subsequently deemed worthwhile to recover/recycle its \(^7\)Li, that could be accomplished by dissolving that salt in water and then adding ammonia – most of the FP and thorium would precipitate out as insoluble oxides/hydroxides leaving the \(^7\)Li in solution as the much more water-soluble lithium fluoride. Boiling that solution to dryness would recover the \(^7\)Li (as \(^7\)LiF) which could then be refluorinated with elemental fluorine to remove any miscellaneous oxides and regenerate « fresh » \(^7\)LiF. However, since AVLIS isolation of \(^7\)Li from natural lithium shouldn’t cost more than about $200 per kilogram (Ault 2012), both \(^7\)Li and thorium recovery/recycle could be put off until most of that salt’s fission products have decayed away.
Appendix III  More opinions about TERRAPOWER’s reactor concepts

The total amount of natural uranium (NU) that has been mined to fuel the USA’s fleet of commercial LWRs generating almost 20% of the U.S. electricity comes to approximately 700 thousand tons. Of those, about 70,000 tons ended up as spent fuel – the enriched uranium fed to the LWRs and then discharged after a few percent of it –mostly $^{235}$U – had fissioned. More than 600,000 tons of that NU ended up as depleted uranium (DU) “waste”. Additional DU was generated by military programs. In principle, liquid metal (cooled) fast breeder reactors (LMFBRs) could burn nearly 100% of such “waste”. However, that cannot be achieved in a single irradiation campaign because neutron-induced cladding damage constrains the burnup level achievable with their solid-type fuels to 15% to 20% FIMA (Fissions per Initial heavy Metal Atom), depending upon how fast the core’s neutron spectrum is. Consequently, high uranium utilization requires multiple fuel recycling. Traditionally, that includes mechanical cladding removal, chemical separation/removal of most of the fission products from the fuel “meat”, addition of depleted or NU uranium make up fuel, fabrication of new fuel elements and finally reloading them back into the reactor core for another irradiation cycle. Although technically feasible, there is a significant objection to fuel reprocessing in Western countries due to economic and proliferation concerns. Fast breeder reactors could, in principle, also operate without fuel recycling; that is, using a once-through fuel cycle as do all of the LWRs presently operating in the USA. Although a discharge burnup of 15% to 20% FIMA is 3 to 4 times higher than that of contemporary LWRs, a LMFBR’s natural uranium consumption is not significantly different from that of a once-through LWR per cycle because the degree of uranium enrichment required to fuel a fast reactor is more than twice that required to fuel a LWR.
Nevertheless, it may be possible to realize a significant increase in the uranium utilization by “reconditioning” fuel that’s reached its radiation damage-limited degree of burnup. The functions of such re-conditioning are to remove a fraction of the fission products, primarily the gaseous ones, and replace the fuel cladding prior to fuel re-use in the reactor. The objective of recent fuel reconditioning research is to overcome material performance limits in a way that cannot extract pure plutonium and is, hopefully, not as expensive as conventional fuel reprocessing. After reconditioning the re-fabricated fuel is loaded back into the core for additional burnup and thereby increasing uranium utilization (Greenspan 2012).

According to Dr. Greenspan, Terrapower’s initial Traveling Wave (TRW) Liquid metal fast breed and burn reactor (LMFB&BR) and its “Stationary Wave” LMFB&BR successor would operate on a once-through fuel cycle burning most of the Pu and minor actinides bred therein without separating them from the fuel. It’s assumed that fuel cladding will last much longer than what’s ever been achieved before after which it will be “reconditioned” in a way that doesn’t isolate plutonium in a sufficiently pure form to be weapons useful.

To me it seems that that is just semantics: someone’s decided to call the “reprocessing” of fuel that’s reached its radiation damage and/or FP buildup limits, “reconditioning” instead.

That’s too “lawyerly” as far as I’m concerned - rather like substituting “LFTR” for “MSBR” or “steam reforming” for “calcination”. Employing slippery terms/definitions and generating deliberately vague documentation is how DOE’s waste management experts managed to convince its Idaho stakeholders that steam reforming would be the best/cheapest/safest etc. way to convert INL’s remaining liquid
reprocessing waste to a competent radioactive waste form (see APPENDICES XII & IV).

I don’t see anything in TERRAPOWER’s MCFR patent applications that I consider “patentable” with the possible exception of their displacement-type “control rod”. Another thing it/they seem to be claiming is the use of a mixed multivalent fuel salt (roughly equal amounts of tri- and quadrivalent uranium) in order to rationalize some of their apparently assumed very low salt melting points\(^\text{248}\). That’d be swell if thermodynamic calculations didn’t suggest that any of the periodic table’s metallic elements (molybdenum, nickel, platinum, palladium, etc.) probably would be oxidized by it, but unfortunately that’s not the case\(^\text{249}\). There’s a reason why almost everyone who’s taken a serious look at the MCFR concept in the past has assumed that essentially all of its uranium must be trivalent resulting in a much more reducing – less corrosive – fuel salt. A mixed multivalent fuel salt work if someone comes up with a super ceramic material to make or line the reactor with, but I haven’t heard about it yet.

Again I feel that a breed and burn MCFR is apt to be superior to any sort of solid-fueled B&B concept for several reasons. However, it’s going to take more than what I’ve seen so far to convince me that TERRAPOWER has come up with the “best” concept.

\(^{248}\) It seems that a better way of arriving at a sufficiently low melting salt mixture would be to substitute \(\text{MgCl}_2\) for some of the \(\text{NaCl}\). Benes’ & Konings suggest that a 0.607 \(\text{NaCl}\), 0.089 \(\text{MgCl}_2\), & 0.304 \(\text{UCl}_3\) (mole fractions) would melt at just 448°C (Benes’ 2008)

\(^{249}\) It may be possible to prevent such corrosion by deliberately maintaining an equilibrium level concentration of the relevant corrosion product(s) (e.g, \(\text{Fe}^{2+}\)) in solution. This is just one of the possibilities that only real-world experimentation can properly evaluate.
Appendix IV Example additive molar volume calculation

Let's determine how much plutonium would be in one liter of a room temperature salt mix containing 5 mole %$^{239}$PuCl$_3$, 28 Mole% $^{238}$UCl$_3$ and 67 mole % NaCl. The principle involved is that to a good 1st approximation, partial molar volumes of a molten salt mix are additive; i.e., mole/cc mix=$\Sigma$fraction mole/cc components

we begin looking up or guessing the densities (g/cc) of the salts going into our mix (I’ve made some educated guesses for this example – the pure heavy isotope salts will be just a bit denser than the natural ones (mix of isotopes) listed in WIKIPEDIA).

The fourth column lists molar volumes of the pure salts e.g for $^{23}$Na$^{37}$Cl=$(37+23)/2.17$ g/cc

<table>
<thead>
<tr>
<th>salt</th>
<th>g/mole</th>
<th>g/cc</th>
<th>cc/mole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu$^{37}$Cl$_3$</td>
<td>350</td>
<td>5.71</td>
<td>61.3 (350/5.71)</td>
</tr>
<tr>
<td>U$^{37}$Cl$_3$</td>
<td>349</td>
<td>5.5</td>
<td>63.5</td>
</tr>
<tr>
<td>Na$^{37}$Cl</td>
<td>60</td>
<td>2.17</td>
<td>27.6</td>
</tr>
</tbody>
</table>

cc/mole salt =
0.05*63.5+0.28*61.3+0.67*27.6= 38.8 cc/mole

g/cc salt =0.05*5.71+0.28*5.5+0.67*2.17= 3.28 g/cc

one liter contains 1000 cc/38.86 cc/mole or 25.7 ΣSalts/liter

weight Pu per liter = 0.05*25.7*239 = 307.1 g/liter
weight $\Sigma \text{HM/l} = 307.1 + 0.28 \times 25.7 \times 238 = 2020$ g/liter

Due to thermal expansion both of these concentration figures would be 10-15% lower at the reactor’s ~700°C normal operating temperature.
Appendix V  QBASIC STARTUP FISSION PROGRAM

REM « Assumes 400 LWRs for first 5 years, then 15 year build-out with initial startup fissile »

REM « After that, all NU goes to building new 1 GWe breeders »

REM « breeder CR can be anything from 1 to 1.3; initial startup fissile (typ. 1900 t, max 2380), NUM = years run time (typ 81) & NU t/a after 20 years to NUM »

INPUT « breeder CR is », CR

INPUT « tonnes available startup fissile is », START

INPUT « numbers of years run is », NUM

INPUT « Tonnes fissile per start is », TON

RTOT=400 :REM « initial 400 1 GWe LWRs, etc.»

FOR X=1 to 5 : NU=NU+64000 : REM « 64000 is tons NU/a required by 400 state-of-the-art LWRs »

NEXT

FOR Y=6 to 20 : NU=NU+64000 : RTOT=RTOT+START/TON/(20-6)

NEXT

INPUT « Tonnes NU mined per year for starting more breeders is », MINEDNU

FOR Z=21 to NUM

RTOT=RTOT+MINEDNU*.007/TON+(RTOT-400)*0.78*(CR-1)/TON : REM « 0.78 is tonnes fissile burned/GWe-year »

NU=NU+MINEDNU

NEXT

PRINT « Total NU after », NUM, « years is », NU

PRINT « Number of one GWe reactors then is », RTOT
Appendix VI  A more realistic tube-in-shell thorium breeder reactor startup scenario

Since the world contains very little $^{233}$U to start with, it would have to be bred in reactors started with either $^{235}$U or $^{239}$Pu. Here’s a concrete example:

Case 1 of Alexander et al’s report (Alexander 1959) assumes the same reactor described in my text, running with $^{235}$U instead of $^{233}$U. Its fuel salt contains 33.8E+19 fissile atoms/cc and its CR is 0.5448 (it’s not a breeder when run with $^{235}$U but does make a good deal of $^{233}$U). So, if we assume the same-sized external plumbing (8m$^3$) as my text’s example’s, it’d require 1.746 tonnes of $^{235}$U to start and would generate 54.48% as much new $^{233}$U in its blanket (170 kg) required to start another same-sized breeder. The best way to see what this means is to write up a little basic program like that in APPENDIX V (see below)

INPUT “input the $^{233}$U fueled breeder reactor’s CR“, CR (any number between 1.00 and 1.19)
INPUT “run time in years “, years
Orig = 64000*0.0071/1.746:  REM  orig is the number of reactors that could be fed/started with the $^{235}$U in 64,000 tonnes of NU (about 260 per year)
Increm = 0.5448*orig:  REM  Increm is the number of new breeders that could be started with the $^{233}$U in the “orig” reactors (about 142 per year)
FOR x=1 to years
N=N+Increm
N=N*CR (adjusts the number of $^{233}$U reactors upwards if CR>1)
NEXT
PRINT “total number 1 GWe reactors in “years, “is” , N+Increm
e.g., for a 50 year run time and a CR=1, we end up with 7349 reactors utilizing the $^{235}\text{U}$ in the same ~64,000 tonnes per year of natural uranium currently consumed by today’s ~400 LWRs. If their CR were 1.05, we’d have 31,427 reactors after 50 years. If it were 1.19, we’d have over 30,000 of them in just 34 years.

Over time, breeding is like the “magic of compound interest” in that it will eventually make its investors rich.

I’ve assumed high-enriched uranium (HEU ≥ 90% $^{235}\text{U}$) starting fissile because low enriched uranium (LEU) within the core would destroy its neutronics and thereby render the system unsustainable. Enriching natural uranium from a LWR’s 5% $^{235}\text{U}$ LEU to HEU, would raise enrichment costs by about 23% (Benedict 1981, p. 671).

Here’s another way to look at it: If it takes 0.312 tonne $^{233}\text{U}$ to bring the breeder version of this thing up to criticality and a $^{235}\text{U}$ fueled version of it has a CR of 0.5448, it should take 0.5776 (0.312*235/233/0.5448) tonnes of $^{235}\text{U}$ to start one breeder.

For 30000 such breeders that’d take the $^{235}\text{U}$ in 2.443E+6 (0.5776*30000/0.0071) tonnes of NU

That’s pretty close to the same amount of NU (400*160* 34 =2.18E+6) predicted by my BASIC program assuming a CR of 1.19.

It could also be started up with “excess” bomb grade Pu though doing so would somewhat complicate “reprocessing” because, unlike uranium, it can’t be easily separated from either FLiBe or 25%ThF$_4$/75%LiF by fluorination.
Appendix VII letter sent to two of DOE’s Inspector General’s lawyers just after my job had been downsized for the last time

(there was no response or any other action taken by them or anyone else in DOE’s/INL’s chain of command – I retired one year later. Most of the names have been X’d out to protect the guilty)

From: Darryl D Siemer [mailto:SIEMDD@inel.gov]

Sent: Thursday, April 07, 2005 10:32 AM

To: XXXXXXXX X XXXX; XXXXX X XXXXXX (the lawyers)

Cc: (everyone in my chain of command)

Subject: more HLW-related waste, fraud, & abuse

The latest YM imbroglio has heightened public awareness of the same issue that I’ve been discussing with you recently; i.e., can folks trust DOE's "science"? Here’s some more background on INL's own little EM-science scandal.

At the beginning of this year one of our calcination experts gave me a copy of the fluidized bed steam reforming (FBSR) "book" that THOR’s chief technical expert had cobbled together a few months earlier (March '04) for a California-based consultant. The cover note prepared & sent along with that "book" indicated that it was being cc'd to DOE-ID's HLW/SBW treatment czar, XXXX XXXX (& only to him).

THOR's “book” made for fascinating reading (to me anyway) because it was the first time that a "proprietary" document describing what had really happened during HAZEN Research Inc.'s 2001 "FBSR mineralization" tests had been released; i.e., how its reactor was really configured, the fact that most of its product (also) consisted of a bulky, flour-like, dust (fines) - not "grapenuts", and that it (also) quickly rocked-up when they tried to produce a sodium silicate-type product. It is also fascinating (to me anyway) because it contains the first document I'd seen which discloses information consistent with the "controversial"
papers I’d written about INEEL’s initial attempt at applying THOR's process to its sodium-bearing waste (SBW)\textsuperscript{3,4}.

Had I been permitted to see this book when Mr. XXXX (\textit{DOE’s local HLW/SBW treatment czar}) first passed it on to BBWI's fluidized bed experts, the job of defending the paper I'd just then written up for the 2004 American Ceramics Society's radwaste symposium would have been much easier. The reason for this is that it seems that no one else (including the reviewers picked for my paper) had apparently seen an unfiltered version of HAZEN's report either - as far as we/they knew, its reactor had produced only a dense, "grapenuts-like", product which official DOE-lab reports had characterized as "better than glass".

Consequently, my paper which suggested that ...

• Mineralization-style FBSR is not an intrinsically "easy" (cheap) process to run
• It invariably produced more dust than "grapenuts"
• It could not turn SBW into sodium silicate, and ...
• Its product is not as "durable" (leach resistant) as previous reports had indicated

… required lots of "defending". (I did, however, eventually prevail – the paper was published\textsuperscript{4}.)

The folks who had volunteered to run ACERSOC's radwaste symposium last year (& this year's too) just happen to work at the same DOE lab (SRS) which had provided THOR with the official reports used to "sell" its process\textsuperscript{5}. By another coincidence, that same lab had recently become DOE's "lead lab" in managing its own steam reforming R &D program - this in spite of the that fact that SRS possesses neither the expertise nor the equipment required to properly evaluate a fluidized bed-based technology\textsuperscript{6}.

Curious.

Even curioser, it seems that as soon as I began to point out some of the inconsistencies between what SRS had published about THOR's process/product & what I had observed during the local test, INEEL's decision makers decided that
they could no longer afford to pay me to provide real-time process (chemical) support during the subsequent FBSR tests to be run for their new customer (SRS). They couldn't afford to pay me to continue to do post-run product characterization work either. (They subsequently also decided that I wouldn't be retained by the lab-side of the new/improved INL either - that's why I'm now a lab-less "cubicle dweller" here at TSB.)

Anyway, last Spring I volunteered to do ”free” post-run characterization of the products of INEEL's CY 2004 FBSR demos & was consequently given samples of everything produced during the rest of those tests. I'm ATTACHING the texts of the notes I sent along with my free analyses/characterizations. Of course, since my results weren't “official”, they were not included in the formal INEEL reports produced after each demo\(^7\). Another reason why my reports/conclusions didn't show up in INEEL's official reports was that its customer had dictated that all such characterization work be performed at SRS - not here where the stuff was being made. (You'll note that I repeatedly chided our team for not duplicating the conditions outlined in THOR’s description of HAZEN’s test\(^2\); i.e., implement 100% recycle of fines back to the reactor. One of the things revealed in the before-mentioned “book” is that we had indeed duplicated HAZEN’s experimental system (almost anyway). What we did differently was to report everything that happened when we tried to run it.)

Everything I've seen indicates that FBSR would be inferior to a properly-implemented vitrification system for INL's SBW.

- FBSR achieves little or no volume reduction (about 6 x less than vitrification)
- It produces more and dirtier (dustier) off gas
- The process itself is apt to be problematic – a rocked-up “mineralized” reactor bed couldn't simply be dissolved-out with dilute nitric acid
- Its product doesn't meet the durability standard that waste forms made from similar radwaste at other DOE sites must satisfy (e.g., Hanford's LLW)
• its product doesn't meet CFR 10-61 disposal/transport criteria (i.e., “no dust”)

• its product doesn’t meet the YM WAC

• and, of course, "stakeholders" on both ends of the waste pipeline prefer vitrification

These observations shouldn’t be too surprising because an independent “Technical Review” had recommended that DOE not attempt to produce a “repository ready” waste form with THOR’s process back in 2000.

Copies of SRS's FBSR product characterization reports were ATTACHED to the note that I sent to you last Thursday. As that note indicates, it’s apparent that some highly-placed individual (i.e., someone who can decide who receives DOE’s EM R&D funding) decided to champion THOR’s technology several years ago and that SRS decided to go after that money. It's also obvious that INEEL's decision makers agreed to keep the lid on what was going on.

It's unfortunate that DOE decided to waste so much time & money on this particular EM boondoggle. It’s more than just "questionable" ethics - the fact that INEEL was not permitted to continue to seek more efficient ways of vitrifying its waste while DOE was encouraging its contractors to “study” FBSR (the status quo approach to vitrification leaves plenty of room for process improvement) means that INEEL may not succeed in converting its “old” reprocessing waste into a stakeholder-acceptable waste form. Since its unresolved “waste issues” continues to be one of the US nuclear power industry’s greatest handicaps, such failure would undermine INL’s chances of playing a leading role in reviving that industry (which, of course, would generate “new” reprocessing waste).

While it's understandable why individuals whose livelihood depends upon remaining in the good graces of our decision-makers might be reluctant to speak up about issues like these, that’s not the situation with me - I’m old enough to retire & have already been “downsized” out of several jobs here at INL.

Where do I go from here? Idaho's Congressional delegation?

2. THOR's 2003 “Tuscon Conference” paper (J. B. Mason et. al., "Steam Reforming Technology for Denitration and Immobilization of DOE Tank Wastes", WM'03 Conference, Feb. 23-27, 2003, Tuscon, AZ.) is a typical example of prior descriptions of the “HAZEN test” in that many of its conclusions are inconsistent with the information in the actual report (doc. TR-SR01-1, Rev 0, "Hanford LAW Waste THORsm Steam Reforming Denitration and Sodium Conversion Demonstration").


5. THOR's characterizations of FBSR calcine as "better than glass" are generally referenced to SRS's reports. The one referenced most often is C. M. Jantzen's, “Engineering Study of the Hanford Low Activity Waste (LAW) Steam Reforming Process, “ WSRC-TR-2002-00317, Westinghouse Savannah River Company, Aiken, South Carolina, July 12, 2002.

6. For example, early last year the materials science experts supported by SRS's steam reforming project wrote up a formal description of how they proposed to spend their research money that year. The centerpiece of their proposal was an multiple step scheme to make a "mineralized steam reformer product with more or less standard laboratory equipment (calcination in a muffle furnace, "hydrothermal" conversion of that calcine, etc.) - not in a fluidized bed reactor. When I pointed out to SRS's "project lead" (Bill Holtzsheiter) that the experimental conditions proposed for that project wouldn't emulate what happens in a fluidized bed reactor (THOR's system), the plan was modified as described in the project's final report (WSRC-TR-2004-00560 Rev A, "Evaluation of Fluidized Bed Steam Reforming (FRSR) Technology for Sodium Bearing Wastes From Idaho and Hanford Using the Bench-Top Steam Reformer (BSR) (U)" December XI (sic), 2004.) The modified scheme involved dribbling a slurry of clay, charcoal, "catalyst", and SBW into a big crucible situated in a preheated muffle furnace. The crucible contained aluminum oxide "bed" granules which were initially fluidized with steam. When the feed mix was added to it, the alumina bed quickly agglomerated (fluidization stopped) which resulted in the formation of a "giant turd" waste form (my appellation) - not a mixture of "grape nuts" and fines.


9."SRS's Steam Reforming Reports - another critical issue", Lotus note to XXXXXX & XXXXX (the lawyers), 31Mar05 (4 ATTACHMENTS)

10. For instance, our leadership decided to not report that the stuff produced by INEEL's first SBW mineralization test didn't exhibit the anticipated degree of "durability" - instead that report (INEEL/EXT-04-01493) indicated that PCT results were "still being evaluated".

11. For instance, the SBW vitrification system outlined in DOE’s ICP RFP “shared documents” website (INEEL/EXT-04-01692) assumes that we would have to build another huge DWPF-type melter. That's not true because glass-making technologies have become more efficient since SRS's melter was designed.

12. Why? That book’s “proprietary” HAZEN test/report (TR-SR01-1) was actually paid for (& therefore “owned” by) WGI/Bechtel National Inc. I probably don’t have to remind you that both of those contractors have "proprietary" interest in this Site too.
Appendix VIII Letter sent to INEEL’s Director circa 2001 (after “separations” & before “steam reforming” was the Site’s “preferred alternative”)

“Ethics & EM – a view from the trenches”

Work’s been pretty slow out at TRA during the last month. The reactor is down again, another ISM audit is pending (audits always generate paralysis), the ventilation system in my lab hasn’t worked for three weeks (INEEL doesn’t seem to be able to maintain blowers anymore), & my usual customers (I’m a chemist) are putting off doing things like submitting samples or doing experiments until the new fiscal year’s funding situation settles down & the auditors go home. Consequently, I’ve had lots of time for “training” – most recently, “Ethics”. For some reason, being reminded about “waste, fraud, & abuse” always gets me pondering about INEEL’s EM programs. Since such thoughts aren’t programmatic & I’ve already burned up too much of my boss’s overhead, I’ve decided to take the day off (PL) to write you this note.

About two months ago I was invited to spend a week in town with about 30 other guys from INEEL and elsewhere (the outsiders included many of the DOE Complex’s glass experts) to try to come up with a sure-fire way to implement “direct vitrification” of INEEL's sodium-bearing waste (SBW). We were told that "direct vit" would be the "preferred alternative" in the upcoming “final” INEEL HLW EIS & were presented with a "90% draft" INEEL engineering document that goes into
excruciating\textsuperscript{250} detail about one way to do it (slurry raw SBW with glass forming agents & sugar in tanks, "characterize" those mixtures, & then feed them directly onto the cold cap of a SRP-type melter @~75 gallons per hour.)

We were also told that we were permitted to think about how the system might be used to treat existing calcines as long as those thoughts wouldn’t impact on how SBW could be treated ASAP. We were divided up into subgroups that were to concentrate upon one aspect of the proposal.

I was probably assigned to the "waste pretreatment" group because I'd just written/distributed a note about the results of the steam-reforming experiment recently run (by SAIC) to verify contentions made in a STUDSVIK proposal that had been sent to me\textsuperscript{251} three years ago.\textsuperscript{252}

Just before we went off to our cubicle, I asked the visitors whether or not calcination (aka, “drying”, "denitration", "incineration", "steam

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\textsuperscript{250} INEEL has a hoary tradition of "paper engineering" projects before doing the R&D needed to test key assumptions (that's how we built a $350 M fuel dissolution facility (FDP) that never achieved better than one-third of its promised throughput). The document I'm alluding to here specifies the size of every room of the proposed facility to the nearest inch & estimates costs to 5 - 7 significant figures. Don't you think it'd be better to determine (experimentally) if we really need (for example) five feed mix tanks before we go into this degree of detail on the paperwork?

\textsuperscript{251} I’d previously written a note to STUDSVIK’s Brad Mason (he’d recently managed a successful fluidized-bed SBW sugar-calcination project for Hanford) pointing out that INEEL would probably not honor its promise to calcine SBW unless an “outside” organization with real credibility & expertise stepped in with “an offer we couldn’t refuse” (or ignore).

\textsuperscript{252} Which I first passed on to INEEL management & then, when nobody paid attention to it, to INEEL Over Sight’s, Kathy Trever.
reforming", etc....) is apt to make the job of converting dilute (solids-wise) nitrate-based liquid into glass easier. They were unanimous, "yes". Consequently, my subgroup (all from INEEL) proceeded to sketch out a scenario that would feed a slurry of SBW, sugar, glass forming agents\textsuperscript{253} into a STUDSVIK-type steam reformer & blow the product ash/calcine directly into the melter\textsuperscript{254}.

When we presented our brainchild to the whole group, it was considered “radical” because what would be going into the melter would have been “characterized” one step before where the folks running the melters at SRS & WVDP do it.

This brings me to one of the reasons for this note – the mind-numbing “conservatism”\textsuperscript{255} evinced by most DOE Complex decision-makers & technical experts. By this I mean unquestioning acceptance of silly (\& often blatantly self-serving) assumptions\textsuperscript{256} that render accomplishing anything unnecessarily difficult, grossly expensive, and often impossible. For instance, in this case, the group was ignoring the fact

\textsuperscript{253} not "frit"- too difficult to keep in suspension – instead, easily suspended/pumped stuff like diatomaceous earth, jeweler's rouge (Fe\textsubscript{2}O\textsubscript{3}), & lithium tetraborate.

\textsuperscript{254} Basically all we had to assume is that what goes into the calciner comes out the other end - minus "volatiles" of course. The British & French screwed up enough courage to make that assumption over a decade ago.

\textsuperscript{255} For instance, the melter subgroup’s technical guru (an outsider) volunteered that an existing high temperature pilot plant melter at his home base could be derated to approximate the characteristics of DWPF for R&D on our problem - do we really want another DWPF?

\textsuperscript{256} For example, for the last ten years, INEEL’s HLW gurus justified their program with the contention that a several cubic mile mountain (YM) would be “too small” to contain 4200 m\textsuperscript{3} (0.000001 mile\textsuperscript{3}) of calcine unless it’s first been “separated”.
that Cogema & BNFL have been successfully making genuinely “hot” (100’s of times more radioactive than DOE's) high-level glasses for over a decade. European melters are fed by close-coupled rotary kiln calciners that simultaneously mix waste with glass forming additives and remove “volatiles” (water, free acid, nitrate, etc.). The reasons why the Brits & French do it this way include; 1) the removal of volatiles improves the productivity of their melters, 2) it simplifies offgas cleanup, & 3) it's intrinsically easier to accurately meter stuff going into a direct coupled calciner/melter system than it is to make calcine separately, "temporarily" store it, retrieve it, mix it with frit, "characterize" the mixture, and then meter it into a melter. In other words they do it that way because that’s what both common sense & economics dictate.

Why would doing it that way here too be “radical?”

In the US, the rationale for saying that the stuff going into our melters has to be immediately “characterized” beforehand is that we assume that it’s impossible to adequately premix our wastes. At INEEL this boils down to accepting the notion that low viscosity solutions containing very little undissolved solids situated in adjacent tanks couldn’t be homogenized by simply pumping them back and forth for a few months (years?) – a patently ridiculous assertion.

If one has the temerity⁴⁵⁷ to ask why “we can’t” mix those liquids (I did), you’re told that the only way to pump them back and forth would

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⁴⁵⁷ Asking “why” in this business automatically makes you “not a team player” – which, in turn, negatively impacts your career.
be to do so with steam eductors ("jets") & since this would dilute waste with condensed steam & the tanks are already “full”, we “can't" do it.

Do you have any idea of how many different ways of pumping liquids have been developed? Couldn’t a “lead lab” adopt one that would allow it to mix its waste?

Some of the other opinions recently expressed by INEEL’s in-house technical/regulatory/safety experts include:

1) “We can’t” efficiently calcine SBW in NWCF
2) "We can’t” recover/recycle NOx from NWCF offfgas
3) “We can’t” recover mercury from NWCF offfgas

There's plenty of evidence that those assertions are all dead wrong. More important, DOE-ID’s acceptance of "we can't"s from its contractor’s in-house experts has repeatedly resulted in its failure to accomplish things it’s promised to do; e.g., 5 years ago, we solemnly promised our then-new Governor (of Idaho) that we'd calcine SBW.

A "lead lab" should keep its promises – if it doesn’t, it’ll lose credibility, then missions, & finally, jobs.

258 The key to efficiently calcining SBW in NWCF (R.I.P.) is precisely what STUDSVIK is now proposing to do (& which the British/ French already do) – add sugar. One of the reasons INEEL recently lost (abandoned) its ability to calcine waste is that its decision-makers refused to implement sugar calcination (their excuse was “safety issues”). Sugar would have also greatly reduced the amount of $NO_x$ dumped into the atmosphere.

259 For example, the shutdown of WERF & NWCF not only affected workers at those facilities but also people who provided services for them elsewhere; e.g., I used to do a good deal of WERF’s analytical work at TRA. Since we’re all still on the INEEL payroll, it’s unlikely that abandoning those facilities/technologies/missions gave much relief to US taxpayers.
Another "we can’t’’ has to do with INEEL's refusal to earmark R&D funds for any HLW management scenario inconsistent with the notions that, a) physical size is the most important characteristic of high-level waste, and, b) glass-making is the “best” way to make any so labeled wastes "road ready"260. Consequently, when DOE-ID finally realized (it took eight years!) that "separations" didn't make much sense, the only alternative that INEEL had generated enough “official paperwork"261 to fall back upon on was "direct vit".

DOE-Hanford's latest public relations disaster262 ought to be a lesson for INEEL. Hanford can't afford DOE-style vitrification & neither can we.

INEEL could become a genuine "lead EM lab" if its leadership permitted it to. One way to make it happen would be to take the blinders off your technical people. There's no valid reason why the research I've done since 1995 (due in large part to the good offices of the Inspector

260 The rationale for this “we can’t” is usually, "there’s not enough money to look at more that one thing at a time”. The fact is that the resources needed to do such research here at INEEL has already been paid for - the equipment, the lab, & my time will cost US taxpayers the same whether they're put to constructive use or wasted. INEEL's bean-counting approach to time/personnel/project management prevents its senior scientific professionals from being more productive because research that's not been "stovepiped” all the way down from HQ can be construed as "time card fraud". It's much safer for individuals to occupy themselves with “training” during slack times.

261 “Official” is the key word here. The bibliography of the recent "Draft INEEL HLW EIS" includes only officially sanctioned/produced documentation, mostly DOE’s reports. Relevant information from other sources (e.g., the National Academy of Science) apparently doesn’t count. Could the reason for this be that much of the unofficial documentation doesn't support the paradigm adopted by the EIS’s authors?

262 i.e., BNFL's first being publicly humiliated & then “fired” for "committing truth" about the cost of vitrification in the DOE Complex.
General & an extremely patient wife) couldn't have been officially sanctioned/funded\textsuperscript{263}. If it had, a lot more could have been accomplished, the tenor of the reports/publications generated would have been different, and INEEL would have something other than “direct vit” on its plate now. I’d also have a legitimate charge number to fall back on during times like this.

P. S. I've written two more "hobby” papers\textsuperscript{264} about how & why INEEL could implement a more productive approach to rendering reprocessing waste road-ready. If you're interested, I'll be happy to send you copies

\textsuperscript{263} Here’s a thought. How about giving your PhD's, let’s say, 60 hours per month of "Professional Development" time to devote to R&D they consider to be consistent with DOE’s professed missions/goals. The number/proportion of "Professional Development" hours should go up every time we abandon another “real” mission/facility, there should be no “carry over” limit on them, & we (the PhD’s) ought to be able to trade ‘em back & fourth to pay for in-house expertise/services.

\textsuperscript{264} Both were presented at this year's American Ceramics Society radwaste symposium.
Appendix IX  Suggestions for improving INL reprocessing waste management

INL’s already calcined reprocessing waste

The fuel reprocessing systems developed by the US federal government’s cold war nuclear defense plants to recover uranium and/or plutonium generated a far greater volume/mass of radioactive waste per unit mass of fuel processed than do those utilized by modern commercial fuel reprocessing facilities. US reprocessing radwaste is less radioactive because: 1) its defense-type reactor fuel was generally not “burned up” to nearly the same degree as are commercial fuels, which means that less fission products were produced per unit mass of uranium processed; 2) the entire fuel rod was usually dissolved (cladding as well as the fuel “meat”) which further served to dilute the waste’s fission products; 3) little attention was paid to minimizing the amounts of solid-forming chemicals (e.g., sodium, aluminum, and calcium nitrates, boric acid, cadmium nitrate, etc.) added to facilitate processing. APPENDIX XI discusses radwaste radiolytic heat generation.

Calcination of this sort of waste was often considered because: 1) weight-wise roughly 80% of it (e.g., nitrate, nitrite, organic chelating agents, water, etc.) is intrinsically volatile; 2) calcination would facilitate its storage because calcines generally occupy considerably less space (typically 15-20%) than do the liquids from which they are made; 3) a calcine would not be as readily dispersed as a liquid if the storage vessel were to be accidentally breached; 4) the relatively low temperatures required to calcine waste (~500°C) would minimize co-volatilization of

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265 However, NRTS/INEL/INEEL/INL was only DOE site that actually did calcine its wastes.
chemical toxins (e.g., Cd) and radionuclides (e.g., $^{99}\text{Tc}$ & $^{137}\text{Cs}$); and 5) calcination would facilitate subsequent implementation of the technologies (e.g., vitrification) which could create a better ultimate disposal form.

![Chemical Process Diagram]

**Figure 29: INL’s New Waste Calcination Facility (Dickey1974)**

Fig. 29 is a schematic of the Chem Plant’s fluidized-bed calciner. Waste solution was sprayed into a heated, air-fluidized, bed of granular solids where it first dried upon the surfaces of those solids after which its nitrate salts decomposed to form oxides. To begin with, its “starting bed” consisted of limestone granules – at steady state, that bed’s particles consisted almost entirely of the waste’s ash-forming components. At that steady-state, feed deposition, particle elutriation, attrition, and deliberate removal of larger particles via overflow resulted in a steady-state particle size distribution. Its bed temperature was maintained at about 500°C via in-bed combustion of kerosene atomized
by oxygen through wall-mounted spray nozzles. The calcined product consisted of a mixture of flour-like fines and sand-like granules which was blown through pipes to binsets (Fig. 22) several hundred feet away where it remains today. The system’s dusty off gas was “wet scrubbed”, passed through silica gel adsorbant beds, and finally HEPA filtered before reaching the atmosphere via a ~300 ft high smoke stack.

The primary weakness of the purely thermal calcination process adopted at NRTS/INEEL was that it could not efficiently deal with wastes in which the molar ratio of alkali metals (primarily sodium and potassium) to polyvalent metal (aluminum, zirconium, iron, calcium, etc.) nitrate salts exceeded ~33%. The reason for this is that sodium nitrate does not thermally decompose at that system’s operating temperature (~500°C) but instead melts to form a viscous liquid which agglomerated (defluidized) the reactor’s bed. In 2000 (after DOE’s “separations” waste treatment paradigm had finally run its course at INEEL), a combination of offgas-related stakeholder issues, INEEL’s unwillingness to sugar calcine its remaining “sodium bearing” liquid waste” (SBW), plus the fact that its calciner was being heated in a way that apparently rendered it an unlicensed “incinerator” caused the site’s decision makers to abandon calcination for “direct vitrification”. Unfortunately, under two years later vitrification was abandoned too because DOE’s topmost environmental management decision maker decided that it would cost too much to implement at INEEL.

The most sensible thing to eventually do (there’s no great rush & no one should pretend that there is) with INL’s calcined wastes would be to fill the reinforced concrete, vaults containing its stainless steel calcine « bins » with a blast furnace slag-based cementitious grout containing finely crushed phosphate rock and vermiculite. That combination of ingredients mixed with enough water to make a stiff but pumpable grout
would set up to form a concrete capable of chemically immobilizing any fission product that might somehow find its way through the walls of those bins thousands of years from now.

Figure 30: INL’s calcine binsets (Staiger 2011, CSSF VII is empty and big enough to contain anything that might be made of its sodium bearing waste (all of them are at least halfway underground)

If that’s too simple, cheap, safe, and logical to be deemed acceptable, the same glass melter that could be used to make phosphate glass gems of INL’s remaining liquid reprocessing waste (see the following subsection) could vitrify its calcines as well. Phosphate glasses are better-suited than borosilicate glasses for such things because they do a better job of retaining transuranic elements (mostly Pu) and anionic species (e.g., halides, $^{99}$TcO$_4^-$, and sulfate).

Better yet, we could slurry up those calcines with the raw SBW and phosphoric acid plus some powdered iron ore and melt the resulting « mud » to make phosphate glass « gems » of 100% of INL’s
reprocessing wastes. Doing so would reduce the total amount of glass required because those wastes’ compositions chemically complement each other\textsuperscript{266}.

As far as such glass’s disposal is concerned, the most reasonable option would be to grout that gem-type aggregate back into the same binsets currently containing the unconsolidated calcines. Failing that, we could ship them down to the NTS’s Area 5 and bury them at the bottoms of a few more Greater Confinement Disposal boreholes (see APPENDIX X).

Of course, if that doesn’t satisfy everyone and we don’t mind waiting for a few more decades, I’m sure that a contractor will eventually promise DOE that it could slingshot them into the sun.

I recently mentioned two other disposal options for such glass in another QUORA answer. https://www.quora.com/Let-s-say-that-we-used-nuclear-energy-on-a-mass-scale-would-Mars-or-the-moon-be-good-resting-places-for-the-radio-active-waste-left-over (warning: some folks might be offended by my suggestions.)

Finally, since DOE has officially declared that INL’s calcines will be hot isostatic pressed (HIPed) in one way or another before 31Dec2035, a more reasonable* way to go about doing it than is currently planned would be to mix them with sufficient dehydroxylated clay and/or class F flyash plus sodium silicate to make a stiff geopolymeric grout that could ________________

\textsuperscript{266} A requirement for good quality, low/easy melting glass manufacture is that the relative amounts of glass network formers (silica and/or P\textsubscript{2}O\textsubscript{5}), alkali (sodium, potassium, cesium...) plus alkaline earth (calcium, etc) elements and polyvalent metals (aluminum, ferric iron, zirconium, etc.) fall within certain ranges. Sodium bearing waste’s non radioactive ash-forming components (Al\textsuperscript{3+}, Fe\textsuperscript{3+} & Na\textsuperscript{+}) would have to be added to any phosphate glass made from just INL’s calcines.
be pumped into the HIP cans. Such grout would set up to form a durable concrete which could either serve as the waste form as-is, or eventually be dried out and HIPed as promised (Siemer 1995*).

*Although DOE has declared that INL’s calcines will be HIPed in one way or another (see 75-FR-1 2010), it must first get permission to do so because HIPing does not satisfy the EPA’s requirement for using the “Best Demonstrated Available Technology” (BDAT which currently still means vitrification). HIPing is usually done by mixing dry powders (in this case, calcined waste with the additives required to form a durable product) and then transferring that mixture to the HIP container (Atkinson 2000). That’s proven to be difficult to accomplish remotely without powder disaggregation, which causes the finished product to be much less durable than it could/should be. If everything is done right (i.e., with the proper additives, a commitment that DOE refuses to make), a HIPed product is apt to be more «durable» than a glass; i.e., last for even more eons after it’s no longer radioactive enough to pose a threat to anyone.

INL’s remaining liquid sodium bearing waste

It’s too late to do what should have happened over twenty years ago; i.e., sugar-calcine it (Loeding 1961, Petrie 1965) and then store that product in INL’s already built-and-paid-for binsets until someone decides for sure what’s to become of its calcines. Since then its calciner (NWCF) was destroyed (decommissioned) over a decade ago and INL’s subsequent steam reforming boodogling hasn’t accomplished much other than making work, its waste management decision makers

267 Almost 100% of INL’s reprocessing wastes had some sodium along with its chemical-cousin, potassium, in them. INL’s SBW had a higher proportion of such alkali-type metals (along with more plutonium and mercury) due to the fact that they had originated from “not first cycle” separation activities (in DOE-world, many things are defined in terms of what they’re not).

268 On 14Mar2019 I got another note (CNN 323337) from the subcontractor currently in charge of INL’s steam reforming project (FLUOR), announcing that DOE is submitting another Class 3
should start over again from scratch. If I were in charge, I’d contact GTS Duratek and see if they might be willing to redo DOE’s one and only «Vitrification and Privatisation Success» at its Idaho Site. SBW is compatible with that same glass formulation and the amount of it to be made is significantly less (Pickett 1995). Since GTS Duratek almost broke even with its $13.9 million fixed-price bid circa 1995, it might be willing to do this project now for, let’s say, $75 million which is surely under 10% of the tax dollars boondoggled away trying to get INL’s steam reformer to work. The one thing that Duratek’s CEO should insist upon though, is that INL’s waste management gurus not be allowed to manage its project.

If in order to save face, DOE’s decision makers insist upon using INL’s billion dollar “reformer”, I’d suggest running it under the same conditions that would have worked with NWCF:

- add jet-type mixers to the SBW tanks so that everything in them, not just supernates, are processed
- heat the reactor via on-bed combustion of kerosene rather than coal - don’t bother with making/adding steam
- run it at about 500 rather than 700°C (doing so will mitigate «bark» formation)
- Mix sugar with the SBW squirted into the reactor calciner via a mixing «tee», not by premixing everything together in a big feed tank.

permit modification request to Idaho’s Dept.of Environmental Quality to make yet another set of 11 major and 1 minor change to that facility.
• Continuously blow its « carbonate product » (calcine) over into binset number 7.

If/when that reformer/calciner plugs up, do the same thing that we did with NWCF: shut it down, dissolve out the bed with nitric acid, return that solution to the SBW tanks, & then start up again. It should not take more than two years to complete the job.
Appendix X Greater Confinement Disposal

The scientific basis of Dr Winograd’s proposal was subsequently thoroughly investigated by SANDIA which renamed it “Greater Confinement Disposal”. In 1984, DOE-NV acted upon this evidence and had a contractor (REECO) bury 500,000 Ci of $^{90}$Sr and 200,000 Ci of $^{137}$Cs in the lower 50-foot sections of two 120 foot-deep, 10 foot-diameter, holes augered into the NTS's Frenchman Flats (Area 5) (Dickmann 1989, Bonano 1991) utilizing the same equipment used to emplace the “devices” which caused that region to appear pockmarked with smaller versions of Dr. Winograd’s suggested Sedan Crater repository site (see « GOOGLE EARTH » 37.178N116.047W). The hotter of SANDIA’s repository-holes contains roughly 3 kilowatts worth of fission product radioactivity – about one-thirty fifth of that in the INL’s entire accumulation of calcined reprocessing waste. Approximately 1000 Ci of transuranic waste including 6 kg of weapons-grade plutonium along with hundreds of kilograms of uranium released by devices that had “fizzled” rather than explode, was buried in another set of four boreholes. The total amount of plutonium in all of INL’s radwaste is about 35 kg - roughly 1% of the amount deposited both within and upon the NTS by DOD/DOE's weapons testing program.

This sort of cheap disposal scheme should eliminate the single greatest action-paralyzer/cost-driver in the USA's approach to radwaste disposal – the ridiculously high costs assumed for the waste's final burial plot.

SANDIA has since released several formal "performance assessments" (PAs) of DOE-NV's GCD (Baer 1993).

They contain the following conclusions:

- No even-moderately-probable chemical/physical/mechanical mechanism other than direct deliberate human intrusion can cause that
repository to fail within 10,000 years. [In this context, "fail" means to not meet the requirements of 40 CFR 191.]

- In spite of the buried fission product elements' (esp. $^{90}$Sr & $^{137}$Cs) far greater initial radioactivities and greater "leachability" as indicated by the leach tests that the developers of high-tech waste forms use to compare their wares at DOE-sponsored radwaste management conferences, those components do not dominate the hazard index of that repository - the much longer-lived « transuranic » (TRU) elements do. This means that short of an actual meltdown$^{269}$, any GCD disposal system (such as Winograd's) suitable for TRU wastes is "conservative" with respect to any fission products or chemically toxic stuff that might be mixed in with it. Most defense-type HLW is mildly « hot », somewhat chemically toxic (contains things like cadmium and mercury), and includes enough miscellaneous transuranic actinides to be deemed « transuranic » (TRU waste) as well.

- The natural mechanism apt to cause the greatest degree of actual leakage of radiation from the GCD to the biosphere during the next 10,000 years involves the gaseous transport of trivial amounts of gases (radon and tritiated water vapor) upwards to the earth's surface - not the leaching of anything down to an aquifer situated more than six hundred feet below the burial zone. Geoscientific research has shown conclusively that there is not now nor has there been for at least 600,000 years (through several comings/goings of glacial ice sheets over most of

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$^{269}$ If the burial crew is even remotely competent (heat generation is easy to measure), a meltdown is impossible.
the USA) sufficient water at the NTS to make the leaching of materials buried at appropriate depths an important dispersal mechanism.

Conclusion: In a competently-sited geological repository, the leach resistance of the waste form material itself is irrelevant.

- DOE-NV and SANDIA are so convinced of the validity of the GCD disposal concept that they have repeatedly and publicly advocated that it be seriously considered for the disposal of the DOE-complex's "orphan wastes"; i.e., wastes for which the existing set of assumptions/laws do not provide even "pretend" repositories like yesterday’s Yucca Mountain (Bonano 1991).

How many boreholes would it take to make a competent repository for the INL’s calcined reprocessing waste? If we assume that decision makers would not want to exceed the heat-loading of the "hottest" existing GCD borehole (three kilowatts) and also that the holes are the same size and depth as were the original ones, the number needed works out to be ~60 (see APPENDIX IX for a discussion of heat issues). The volume represented by the lower 50' sections of 60 individual, ten-foot-diameter, boreholes is 6660 m³ – about the same as that of the concrete needed to "encapsulate" all existing ICPP waste.

What would such a repository cost US taxpayers? Sandia reported that each of the boreholes in its original GCD cost $20,000. If we apply a 5% inflation factor compounded for 38 years to sixty times $20,000, the cost of the proposed repository works out to $7.7 million dollars. That is approximately 0.4% of INL’s current annual payroll cost.

Most of the reasons why an augered-shaft GCD repository would be "better" lie in the intrinsic nature of NTS alluvium. First, both because the soil in question is extremely dry and the little rain that does fall in « Area 5 » (about 10 cm/year) evaporates before it can reach a
significant depth, convective transport of buried material is negligible. Diffusion, the only other natural process allowing radionuclide migration, is vanishingly slow in vadose-zone (dry) soils possessing high ion-exchange capacity. Second, plant populations are very sparse, not of the variety eaten by humans, and their roots don’t go down 100 feet - so the food poisoning « what if » doesn’t hold water.. Third, because the NTS’s alluvium accumulations cannot support open fractures ("cracks"), any future tectonic activity in that area would have minimal consequences. [This is not a trivial point because it means that no hypothesized "crack" could channel water from a hypothesized future flood directly through the burial zone to the underlying aquifer – flood water would have to diffuse downwards uniformly. Vulnerability to hypothetical "failures" caused by hypothetical cracks is a fundamental weakness of brittle, hard stratified rock, repository sites such as Yucca Mt, which is what made it so difficult (and terribly expensive) to "prove" that it could work for 10,000 years\textsuperscript{270}. Fourth, the vertical-shaft design of a GCD repository minimizes the footprint of the disposal system which means that the probability of inadvertent human intrusion is minimized relative to mined repositories. Fifth, the geologic setting of the NTS's alluvial plains is such that potential future change, natural or man-made, would have little effect on overall system performance. Sixth, the thick alluvial deposits in question not only happen to be situated in the driest part of the USA's driest desert, they have also been thoroughly contaminated by about 925 nuclear "events," over 120 of which were deliberately set off above ground. If there is any other place

\textsuperscript{270} DOE’s “trans scientific” YM modeling exercise never did (or could) succeed in “proving” that it couldn’t fail any more than I/you could prove that a meteor couldn’t possibly take out Airforce One next Tuesday.
within the United States that's apt to be considered by the average US citizen/taxpayer/voter as a better place for a nuclear garbage dump, my studies have not yet revealed it. Seventh, it is simpler and therefore safer to emplace a drum (canister) of waste straight down a shaft and then backfill it than it would be to emplace the same object into one of the maze-like configurations usually envisioned for engineered geological repositories. Eighth, and perhaps most important, unlike the situation with Yucca Mountain, a GCD repository has already been implemented and already performance-assessed with real waste.

It would be both cheap and easy to improve upon DOE-NV's original GCD. For example, since it happens to be situated where the water table is relatively shallow by NTS standards (780 feet down), it cannot be fairly characterized as the most "conservative" site therein. [The portion of Yucca Flats that Winograd proposed for the nation's TRU repository has a water table 2½ times deeper]. The existing GCD was not sited at Yucca Flats because the same hydrogeological features that make it the best place to site a GCD also made it the most "defensible" place for DOD/DOE to do underground nuclear testing – the overriding mission of the NTS (nobody pulls more political weight at the NTS than does the US military). Secondly, SANDIA's performance modeling indicates that it would probably be better to bury wastes somewhat deeper than that existing GCD’s 70'. Twenty years ago REECO engineers told me that the NTS possessed drilling rigs capable of drilling 12-foot diameter holes to depths exceeding 2000 feet (they were originally built to emplace big nuclear "devices" and test equipment). This means that waste forms could easily be buried at any depth considered optimal by Sandia’s performance assessment modeling experts [probably below the
30-meter figure that the NRC considered to be the lower bound of "near surface"]271. Next, since competent cementitious waste forms would be buried instead of raw waste, the disposal system should be credited for the well-documented retardation properties of the concrete matrix. [SANDIA allowed no "waste form credit" in its performance assessment of the existing GCD; i.e., modelers assumed that the waste is neither solidified nor "contained" within any engineered barrier]. Finally, it would be a very simple matter to pour a cementitious grout around and over the so emplaced drums of waste before backfilling those holes. Doing so would meld the individual drums of concrete into huge monoliths having a much smaller surface:volume ratio to leach from and, more importantly, would) provide enough chemical buffering to stabilize the entire system for millions of years.

As a concession to Nevada’s' political sensibilities, I should point out that if the cluster(s) of boreholes constituting such a new repository were to be drilled over existing bomb "chimney(s)" , the concrete caps that would be put over them to direct rainwater off to the side would also direct that same rainwater away from the unremediated waste left by the original "events". It is also worth noting that waste disposal would provide a new and worthwhile mission for the hundreds of Nevadan site workers who are probably wondering how they are going to support their families now that the USA’s cold war-inspired bomb testing is over (I hope) and DOE’s Yucca Mountain study has ended. Finally, I should mention that no European nation has any such easy choices to make regarding the siting of their radwaste repositories. No EU nation

271 Most of the approximately 240,000 m$^3$ of radioactive waste buried in INL’s “Radioactive Waste Management Complex” is covered with under one meter of soil.
is blessed with a large desertified region possessing the requisite hydrogeology and none have already contaminated large areas of their own soil with hundreds of nuclear blasts. The USA’s decision makers ought to consider its Nevada Test Site (NTS) to be yet another of their country’s unique natural assets and put it to productive use.
Appendix XI  How « hot » are DOE’s high level wastes?

The absorption of ionizing radiation by anything generates heat energy within it. Safe dissipation of such heat is a key criterion in the design of nuclear equipment, waste form materials, and waste repositories.

According to WHC-SO-WM-EV-102, REV 0, (« Single-Shell and Double-Shell Tank Waste Inventory »- Google it), in 1995, Hanford’s roughly 54 million gallons of tanked reprocessing wastes had a total of about 3.3E+7 curies of $^{90}$Sr and $^{137}$Cs in them. Since there’s 264 gallons per cubic meter, both isotopes have ~30 year half lives, and Hanford’s wastes have decayed for another 24 years (i.e., is now 57% [0.5^(2019-1995))/30]) as hot as it was in 1995), this means that Hanford’s HLW now contains an average of about 92 Ci/m$^3$ of $^{90}$Sr and $^{137}$Cs [0.57*3.7E+7/54E+6/264]. Because the decay of both isotopes generates about one million electron volts (ev) (1.6E-13 Joule) and one Curie =3.7E+10 decays per second, that much activity translates to a heat generation rate of about one half watt/m$^3$. In light of the fact that a burrowing mouse generates more heat than that, it’s not tough to understand why it would now be perfectly safe to grout glass gem « aggregate » made of such waste back into Hanford’s tanks.

According to INEEL/EXT-98-00455, Rev 4 (Calcined Waste Storage at the Idaho Nuclear Technology and Engineering Center - Google it), >99% of its radioactivity is due to the decay of roughly 2000 Ci/m$^3$ each of $^{90}$Sr and $^{137}$Cs. That translates to a heat generation rate per cubic meter of about 23.6 watts [((2000+2000)*3.7E+10*1.6E-19].

On the other hand, the concentrated first cycle raffinates going into a typical commercial fuel reprocessing plant’s glass melter would have roughly one mole per liter of fission products in it. Assuming that 10%
of those fission products still behave like $^{137}$Cs and $^{90}$Sr (haven’t decayed yet), the heat generated by 1 cubic meter (1000 liters) of such HLW would be about 7058 watts

$$[1000 \text{ l/m}^3 \times 1 \text{ mole/l} \times 6.023 \times 10^{23} \text{ atoms/mole} \times 1.6 \times 10^{-19} \text{ J/ev} \times 1 \times 10^6 \text{ ev/atom} \times \ln2/(3600 \times 24 \times 365 \times 30)]$$

- that’s fifteen thousand times « hotter » than is Hanford’s HLW

$$\text{decay/s} = \text{Bq} = \text{number of radioactive atoms} \times \ln2/\text{half life in seconds}$$

(where ln2=0.693)

Appendix XII  How the nuclear industry’s « experts » may mislead us

The purpose of this little rant is to demonstrate that understanding a procedure’s technical details is important in determining whether or not what you are being told supports the teller’s contentsions.

During the time that INEEL served as DOE’s lead radioactive waste management lab, the key criterion for evaluating candidate radioactive waste form materials was their performance on the «Product Consistency Test » (PCT). That test as performed as follows:

- the sample is shattered and then ground to a powder
- particles between 75 and 150 microns in diameter are isolated by running the powder through calibrated screens
- that size fraction is subjected to a quick rinse with water or ethanol to rinse off fine dust after which it is dried (such rinsing was originally left to the discretion of the analyst)
- the rinsed/dried particles are weighed into into a Teflon or stainless steel « bomb » and 10 times as much deionized water is added
- The bomb is sealed and put into a 90°C oven for exactly one week
- Its contents (water leachate plus undissolved glass) are then filtered to isolate the liquid (leachate)
- That leachate is analyzed to determine the fraction of each of the sample’s constituents solubilized (leached)

The pass/fail criterion for DOE’s HLW glasses (both then and now) is whether a higher fraction of the sample’s alkali metals (usually its most intrisically leachable/soluble major constituents) ends up in solution than does from a portion of its benchmark « Environmental Assessment » (EA) standard glass run through the same protocol. About 12% of EA
glass’s alkalies generally dissolve (EA glass is not a very durable glass – it’s an « easy » standard).

The PCT is relatively quick/easy to perform and, if the sample in question is a glass (homogeneous frozen liquid), generates a genuinely meaningful result because everything within them is « released » at about the same concentration-normalized (fractional) rate ; i.e., if 10% of the specimen’s alkalies end up in solution, 10% of the radionuclides and chemical toxins have been «unsequestered» as well.

The rationale ginned up by DOE’s experts to support its contention that « mineralized » steam reformer product would be « better than glass was that it is «... primarily composed of nepheline (ideally NaAlSiO₄) and the sodalite family of minerals (ideally Na₈[AlSiO₄]₆(Cl)₂ which includes nosean (ideally Na₈[AlSiO₄]₆SO₄). Semi-volatile oxyanions such as ReO₄⁻, TcO₄⁻, are expected to replace sulfate in the larger cage structured nosean and halides such as I⁻ and F⁻ are expected to replace chlorine in the nosean-sodalite mineral structures – thereby immobilizing them. »

In reality that’s not the case. When INL’s SBW simulants were «reformed» the majority of the stuff going into the « product » receivers was « fines » consisting of <10 micron-sized, poorly mineralized dust mixed with lampblack-like elemental carbon particles. X ray diffraction spectrometry (XRD), the technique utilized for characterizing the minerology of such things, is « blind » to much of that stuff because it’s not very crystalline and XRD doesn’t identify what’s within its crystalline moiety (e.g. chlorine, ⁹⁹Tc, or sulfate) - only its structures (XRD is a qualitative not quantitative analytical method).

The PCT protocol’s ’s 75 micron lower particle size cut-off dictates that the analyst deliberately not test ~2/3’s of what most such steam
reforming’s demonstrations actually produced – its relatively poor-performing fines product fraction. That fraction contained the bulk of the waste’s intrinsically volatile constituents (e.g. cesium, iodine, chlorine, sulfur, technetium, cadmium, etc.) remaining in either of its solid products and also tends to be more water soluble (leachable) than the coarser sand-like bed product particles (Siemer 2005).

Furthermore, almost all of the solids produced by a steam reformer are multiphasic which means that their constituent elements are present in different forms exhibiting different characteristics - not dissolved within a homogeneous frozen liquid (glass). This, in turn, means that literal adherence to the formal PCT protocol is apt to generate wildly optimistic (misleading) results. For example, a quick water leach of either of the products of INEEL’s (fines and its « grapenuts like » granular product) steam reforming demonstrations removes most of their chloride (Siemer 2005). Since the original version of ASTM C1285-02 (the one used during the crucial initial decision-making phase of the project) left sample powder-washing to the discretion of the analyst, an “official” test performed for the purpose of determining the leach rate of chloride could be done on material that no longer actually contained chloride – which, in turn, means that the final analysis’s apparently very low Cl⁻ result might be (and was) interpreted to mean that steam reforming had immobilized it within a leach resistant tectosilicate mineral (sodalite, Na₈Al₆Si₆O₂₄ Cl₂) . The same rationale supported claims that other tough-to-vitrify species (e.g. sulfur and ⁹⁹Tc) would end up within another leach resistant « cage mineral » (nosean).

Additional deliberate confusion was generated by normalizing the PCT’s raw “fraction leached” results to a bogus surface area.

For example, one gram of cubic mid range-sized, 2.6 g/cc PCT sample particles (diameter =0.01125 cm [0.015 +0.0075)/2]), would have a
geometric surface area of 205 cm$^2$ \[
[6*0.01125^2/0.01125^3/2.6].
\]
However since a steam reformer’s solid products are intrinsically porous, their BET surface areas are far larger than their geometric surface areas$^{272}$.

In a typical such leach test that I’d performed myself (Siemer 2005), 12.5% of the sodium in a 50:50 mix of INEEL’s pilot plant steam reformer’s fines & bed products dissolved. If that figure is normalized to its « geometric » surface area, its area normalized leach rate in the usual units works out to 6.1 g/m$^2$/week \[
[0.125/(205/10000 \text{ cm}^2/\text{m}^2)],
\]
about the same as that of DOE’s go/no-go standard glass. However, to make the steam reformer product’s granulated product fraction seem superior, DOE’s leach test experts at both SRS and Hanford decided to normalize fraction-leached PCT results to a “total” (BET) sample particle area$^{273}$ rather than upon a figure based upon particle size and density as the PCT’s protocol dictates (Pariez 2005).

$^{272}$ The BET surface area of a 50-50 by weight mix of the as-generated fines and bed products produced during the “optimized” demonstration described in APPENDIX IV was 83m$^2$/g. The samples subsequently characterized by SRS were first subjected to an overnight “cook” at 500°C which would almost certainly serve to reduce BET-type surface areas as well as burn off the “coal”. Nevertheless, they still exhibited BET surface areas over a hundred times greater than would the same sized glass particles.

$^{273}$ The BET measures the amount of an inert gas condensing upon on a powdered sample at a temperature near the boiling point of that gas. The amount so condensed is measured by the pressure reduction within the system when sample is introduced. All open pores, inclusions, irregularities, etc., penetrable by the inert gas (usually nitrogen) are accounted for which means that anything that’s intrinsically porous (e.g., charcoal, silica gel, or FBSR calcines) exhibits a far larger BET than geometric surface area.
Reporting such « normalized » results made that stuff appear to be >100 times more leach resistant than DOE’s benchmark glass and therefore gave great reassurance to those analysts’ decision-maker customers. However, it’s also transparently(?) silly because any material possessing a surface area/gram greater than about 1640 cm$^2$/g (205*1/0.125) could totally dissolve during the PCT and still be characterized as “better than glass” (this little technical detail was never pointed out (realized?) by the experts responsible for writing/reviewing such reports$^{274}$).

Even more important, it is unreasonable to characterize a “mineralized” (or any other) calcine as superior to glass (or even to a properly made concrete) based solely on PCT results – even results obtained with a “conservative” version of it (Siemer 2005). The reason for this is that glass is intrinsically monolithic and calcine is intrinsically dust-like. Since real world leaching occurs at « outside » surfaces, the surface area of the intact waste form is what would count in a repository. For example, a one million-gram glass monolith (smaller than most real or proposed US glass waste forms) possesses a geometric surface area of about 3 m$^2$. Its “real” surface area isn’t much greater than that because glass is basically just a non porous super-viscous liquid (Wesson 1983). About one gram (exact amount depends upon how its area is measured) of INEEL’s mineralized FBSR test products possessed that much surface area.

$^{274}$ A reason for this was identified by Upton Sinclair about a century ago: "It is difficult to get a man to understand something, when his salary depends upon his not understanding it"
Appendix XIII  Example of a promising concept that needs experimental verification as soon as possible

The data in Table 7 (below) is excerpted from ORNL 2751 (Alexander 1959). Its numbers were based upon calculations performed with a 31-group, multiregion, spherically symmetric, diffusion code UNIVAC program named “OCUSOL”. Group-averaged cross sections for the elements of interest were based on then available data. Where such data were lacking, reasonable interpolations based upon resonance theory were used. Estimated neutron reaction cross sections were made to agree with measured resonance integrals where available and saturations and Doppler broadening of the resonances in thorium as a function of concentration were estimated.

<table>
<thead>
<tr>
<th>Table 7</th>
<th>ORNL 2751’s Case 35 Spherical “clean core” two salt thorium breeder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core diameter ft</td>
<td>3.0</td>
</tr>
<tr>
<td>Mole% ThF₄ in fuel salt</td>
<td>0</td>
</tr>
<tr>
<td>Mole% ²³³U in fuel salt</td>
<td>0.592</td>
</tr>
<tr>
<td>²³³U atoms/cc of fuel salt x10^19</td>
<td>21.1</td>
</tr>
<tr>
<td>Neutron absorption ratios*</td>
<td>Leakage***</td>
</tr>
<tr>
<td>²³³U (fissions)</td>
<td>0.8754</td>
</tr>
<tr>
<td>²³³U capture (n,y)</td>
<td>0.1246</td>
</tr>
<tr>
<td>Be, Li, and F in fuel salt</td>
<td>0.0639</td>
</tr>
</tbody>
</table>

*ORNL assumed 2.1973 neutrons/fission (=’s a total absorbed per neutron absorbed by ²³³U)

**ORNL assumed a one third inch thick INOR 8 core tank

***ORNL assumed a two foot-thick, 25 mole% ThF₄/75mole% Li F, blanket salt

The reasons why tests verifying the conclusions of this particular set of ORNL’s calculations should receive immediate attention include:

• If Weinberg’s team was right, then the full-sized tube-in-shell concept that I’ve described (Fig. 14) is very likely to behave as predicted and therefore represent the “best” way to implement a sustainable nuclear renaissance
• It would be a relatively cheap system to both build and operate (much cheaper/simpler than any sort of solid-fueled test reactor)\textsuperscript{275}

• Its operation would enable the generation of real data\textsuperscript{276} relevant to every aspect of both building and operating breeding capable MSRs

• Systems like it could be readily scaled up by substituting one or more cylindrical cores for the single spherical core contained within its blanket salt tank

The reasons why it should be at least as capable as ORNL’s modelers predicted include:

• It seems that ORNL underestimated the number of neutrons generated per $^{233}$U fission (i.e. $>2.3$ rather than $2.2$) which would boost Table 7’s predicted CR (0.9722) to well over 1.0 (Uranium 233, 2019)

• There’s no compelling reason to assume that a 3 foot diameter core tank immersed in a blanket salt would have to be one-third inch thick – a thinner core tank wall would also boost CR

\textsuperscript{275} For instance, its core would require only about 32.6 kg [$400 \text{ liters} * 1000 \text{ cc/liter} * 21.1E+19 / 6.023E+23 * 0.233$] of $^{235}$U fissile to achieve criticality (operate). Depending upon how much heat is to be generated/dissipated during its testing, that figure would be somewhat bigger. For example, if we assume that 9 cubic meters of outside core volume is sufficient to remove 3 GWt (the figures estimated for the EU’s MSFR), a 50 MW test reactor would require 150 liters of additional core salt boosting its total fissile requirement to 45.6 kg. Similarly the Hastelloy N “supermetal” required to make a three foot diameter, one quarter inch thick spherical core tank would weigh about 637 kg and cost about $16,000 (see https://www.alibaba.com/showroom/hastelloy-n.html). If 316 stainless steel (SS) were to be substituted for it instead, its core tank would cost about one fifth that much. With proper redox control, 316 SS is probably good enough.

\textsuperscript{276} Its salt streams would provide something real for the folks working out any fluoride salt MSR concept’s fuel clean up and waste management schemes to work with. Its behavior would provide updated neutronics data enabling better prediction of that of a full sized system. Finally, realistic corrosion/neutron damage rate data would be generated – almost 100% of the MSR-relevant recent corrosion testing has been done “cold” (no neutrons) with pure salts containing no fission product surrogates.
• There’s also no compelling reason why the blanket salt tank couldn’t be considerably bigger which would reduce neutron leakage and therefore again boost CR
Appendix XIV  INL’s steam reforming process

During the 1990’s, a Swedish firm, STUDSVIK, developed a process to “burn” the organic wastes generated by civilian nuclear fuel cycles (mostly the ion exchange resins utilized to purify LWR coolant water) in a way that avoided the negative connotations that had come to be associated with “incineration”\textsuperscript{277}. It utilized superheated steam (hence “steam reforming”) to decompose such materials to simpler molecules (methane, hydrogen, carbon monoxide, etc.) under the conditions proposed for converting “biomass” to gaseous fuels. When it became apparent that US DOE wanted a substitute for calcination too, the same(?) process was suddenly construed to be the “best” way to treat salt-type wastes as well. Consequently, in 2002 Studsvik joined with Westinghouse Government Environmental Services Company LLC to form a new company, THOR Treatment Technologies to further develop, promote and deploy that technology (see THOR no date).

The resulting fluidized bed steam reformation (FBSR) process possessed four key virtues: 1) its “Denitration and Mineralization Steam Reformer” (DMR) would not directly oxidize organic components of such waste streams with elemental oxygen, hence it’s not waste

\textsuperscript{277}  By circa 2000 DOE’s decision makers had buckled under to its anti nuke critics and promised that it would no longer “incinerate” wastes. Incineration (burning) was then and is still the best way to convert anything that’s “organic” (burnable) to a harmless, low volume, ash. The best way to do it with anything that’s not too radioactive is to substitute that waste for some of the coal or oil heating a cement plant’s rotary kiln. However, to enhance “productivity” & avoid over-regulation hassles most of the incineration currently being done is with purpose-built systems that don’t burn garbage nearly that cleanly (see APPENDIX XVI for an example of an especially timely application).
“incineration” (real DOE tank wastes contain little or no organic matter); 2) since the immediate solid products produced under its strongly reducing (fuel>>oxygen) reaction conditions were mostly carbonates, not oxides, it wasn’t “calcination” either; 3) since alkali nitrate salts should decompose under such conditions (eventually anyway), it’s supposed to prevent bed agglomeration and simultaneously eliminate the offensive plume of NOx emitted by INEEL’s traditional approach to radwaste calcination (the same things that sugar calcination would have accomplished); 4) the inclusion of powdered clay along with the solid fuel granules employed to provide reaction heat, serve as a reductant, and generate a clean-burning intermediate offgas, was supposed to convert SBW to a poorly soluble “Grapenuts-like” mineralized product purported to be a “better than glass” disposal form; and 5), several of the especially troublesome (to glass makers) anionic components of DOE’s salt wastes (e.g., sulfate and chloride).

278 This is another example of something being characterized in terms of what it’s not rather than in terms of what it is. Reforming is nicer sounding too – Norway “reforms” its murderers instead of “frying” (incinerating?) them in electric chairs.

279 (coal, charcoal, etc. – a solid reductant constitutes the “novel” feature of THOR’s patent)

280 Sufficient oxygen was added to burn enough of the coal (certainly not all of it) to keep the DMR’s reactor hot enough to function.

281 The final version of THORT’s steam reformer (THOR no date) differs in how its DMR’s off gas is burned. After most of the dust is removed via cyclones & blow back filters and sent to a “product” container, the DMR’s gaseous products (mostly steam along with nitrogen and combustible hydrogen, ammonia, carbon monoxide, hydrogen, cyanogen, etc.) passes into a second even hotter (~1000°C) “Carbon Reduction Reformer” (CRR - another fluidized bed reactor) to which sufficient additional oxygen is added to burn it to a mixture mostly comprised of elemental nitrogen, excess oxygen, carbon dioxide, and water vapor.
were also supposed to be simultaneously sequestered within leach resistant aluminosilicate “cage minerals”.

The following pages (smaller font) are excerpted from a report that I wrote/presented in 2004 about experiments performed to determine whether the product(s) of a local “demonstration” of THORT’s technology could be rendered “nondispersable” with cements (Siemer, Grutzeck, and Scheetz 2004). There’s an error in its second footnote: I subsequently discovered that THOR’s “open access” technical reports had misrepresented both its subcontractor’s (HAZEN’s) experimental system and its products – fines were apparently never successfully 100% recycled and thereby just one, “grapenuts like” product produced as
repeatedly claimed.

During Dec. 2001 several tests of Studsvik’s “mineralization” process were performed by Hazen Research, Inc, of Golden CO. 570 liters of a concentrated (~44% solids) aqueous salt solution representing a typical “low level” Hanford tank waste were processed in a six-inch diameter reactor. The primary component of this simulant was ~ 8 molar sodium ion balanced by (in order of decreasing concentration) hydroxide, nitrate, carbonate, nitrite, carbonate, aluminate, sulfate, fluoride, phosphate, and chloride. It also contained lesser amounts of several other metals plus about 80 grams per liter of an assortment of the organic chelating agents used in Hanfords’ processes. The reactor’s alumina bed particles were fluidized with superheated steam and ground coal was added to create a strongly reducing environment. Sufficient kaolin (nominally Na₄Al₄Si₄O₁₅·OH₈) and powdered quartz were slurried with the waste simulant to produce a product with roughly the same gross composition as nepheline, NaAlSiO₄. Samples of it were submitted to the Savannah River Technology Center which subsequently issued a report supporting Studsvik’s claims and recommending that DOE pursue the technology.

Table 1: INEEL tank WN 180 SBW simulant

<table>
<thead>
<tr>
<th>CATIONS</th>
<th>Molar grams/mol</th>
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<tbody>
<tr>
<td>Acid (H⁺)</td>
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<tr>
<td>Alumnum</td>
<td>0.66/17.9</td>
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<tr>
<td>Boron</td>
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<td>Cesium</td>
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<tr>
<td>Chromium</td>
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<tr>
<td>Copper</td>
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<td></td>
</tr>
<tr>
<td>Iron</td>
<td>0.022/0.21</td>
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</tr>
<tr>
<td>Lead</td>
<td>0.0013/0.274</td>
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<tr>
<td>Magnesium</td>
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<td>Manganese</td>
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<td>Potassium</td>
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<td>Rhenium</td>
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<td>Sodium</td>
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<tr>
<td>Strontium</td>
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<td>Zinc</td>
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</table>

ANIONS

| Chloride         | 0.03/1.06       |  |
| Fluoride         | 0.047/0.90      |  |
| Nitrate          | 5.3/330         |  |
| Phosphate        | 0.029/2.74      |  |
| Sulfate          | 0.070/6.72      |  |
| Water            | 40.6 (731 g/l)  |  |

In January 2003, a demonstration of how it could deal with a representative INEEL liquid SBW (Table 1) was performed at the Science Applications International Corporation (SAIC) Science and Technology Application Research (STAR) center located at Idaho Falls, Idaho. This test was performed under conditions mutually agreed upon by THOR and INEEL personnel and, while it was subsequently deemed “successful”, it was also agreed that there was a good deal of room for improvement. Consequently, in November 2003 a two week-long “optimization run” was run at the same facility. This paper describes what was produced while the reactor was being run with a mineralization flowsheet (i.e., with clay added to the SBW) and how cementitious technologies could convert this material into a superior waste form.

Experimental: Figure 1 depicts the FBSR reactor used for SAIC/INEEL’s most recent FBSR test. It basically consists of a 30 inch length of six-inch internal diameter pipe reaction zone situated under a five foot-long, expanded (12 inch diameter) particle disengaging (or “freeboard”) zone.
Both sections are made of an especially corrosion resistant INCONEL alloy. Table II lists typical operating conditions. One of the reactor’s two feed streams consisted of an aqueous slurry comprised of various proportions of sugar-syrup with Table I’s SBW simulant plus kaolin. This cream-like slurry was sprayed into the lower end of the reaction zone with a pneumatic nebulizer utilizing nitrogen as the motive gas. The other feed stream consisted of coarse granules of activated charcoal plus occasion additions of an iron oxide “de-NOX catalyst”. The external surfaces of the reactor & its disengaging head were covered with clam-shell electrical heaters. A distributor plate situated immediately above the flat bottom of the reaction zone introduced superheated steam which served both to fluidize the bed particles and provide a portion of the heat required for the strongly endothermic “reforming” reactions. Any additional heat required to maintain the system at the desired temperature was provided by “reforming” elemental oxygen added to this steam. A cyclone served as the primary collection system for the “fines” (comprised of small particles of the reactor’s product plus elemental carbon dust) elutriated from the reactor. A screw auger continuously recycled that dust back into the base of the reactor. Particles too small to be captured by the cyclone were collected by a bank of sintered metal blow-back filters situated within a cyclone-shaped housing. This portion of the reactor’s “fines” plus the material retained in the bed constitute its two product streams.

Typical FBSR reaction conditions
- Gases: 7 kg/hr steam + 3 kg/hr N₂ + 1 kg/hr. O₂
- Liquid Feed: 4.5 kg/hr SBW/clay slurry + 3 kg/hr of 55wt% sucrose syrup
- Solid Feed: varying amounts of coarse activated charcoal + occasional additions of FeOₓ
- Temperature: ~720°C

Filtered offgas was diluted with propane plus excess air and passed into a ceramic-lined thermal oxidizer large enough to provide a mean gas residence time of approximately one second at 1000°C. After the temperature of the burner’s offgas was lowered to roughly 300°C by spraying water into it, it was sucked through a venturi scrubber into the scrub tank. The

1 Occasionally this auger would be reversed in order to collect samples of the cyclone catch.

2 The fact that this portion of the reactor’s fines was not recycled to the reaction zone constitutes the most significant difference between the HAZEN and SAIC/INEEL tests – HAZEN produced only a “bed” product.

3 290 grams of kaolin were added per liter of SBW: this much clay increases the volume of the liquid by 10% and its SpG from ~1.25 to ~1.38. The sugar feed rate varied considerably but was always well in excess of that required for stoichiometric reduction of nitrate to elemental nitrogen.
quenched/scrubbed gas exiting that tank was passed through a demister, reheated to roughly 120°C to prevent condensation, sucked through a three-stage bed of activated charcoal, and, finally, blown through HEPA filters to the stack.

Since the primary purpose of this paper is to discuss “monolithification” of the reactor’s product, its description of how the “reformer” itself performed will be limited to the following observations:

1. The processing of sufficient SBW/clay slurry (498 kg) to generate 126 kg of mineralized product produced a total of approximately 74 kg of “fines product”, 3.6 kg of cyclone dust samples, and 44 kg of “bed product”\(^4\)
2. On-the-fly samples of both products during the run generally contained a substantial amounts of elemental carbon (dust in the fines fraction, 1-5 cm chunks in bed samples) – the amounts of “product” carbon depended upon the feed rate of activated charcoal to the reactor
3. Bed product samples generally contained mineralized agglomerates\(^5\) which tended to grow larger and more numerous as the run continued

\(^4\) This figure (44 kg) does not count the ~52 kg of ~0.5 mm-diameter, sintered alumina “starting bed” charged to the reactor on two separate occasions.

\(^5\) The water solubility and carbonate concentration of these lumps (both low) were similar to those of the non agglomerated bed material
4. On two (three?) occasions those agglomerates grew large enough to cause bed defluidization which immediately shut the process down.

5. Regardless of charcoal feed rate, “on the fly” samples of either solid product fraction never contained more than 0.1% residual nitrate (or nitrite) – generally none at all.

6. Offgas samples taken upstream of the offgas burner generally contained several thousand ppm (by volume) ammonia plus readily detectable concentrations of HCN. The ammonia concentration correlated directly with charcoal feed rate.

7. Total NO\(_x\) (NO\(_2\)+NO) concentrations at the same point was generally somewhat higher than that of ammonia and inversely related to charcoal feed rate.

8. The scrub liquor was always strongly acidic – pH generally less than 2.5 – and contained very high concentrations of sulfate, phosphate, chloride, and cesium relative to iron, sodium, aluminum, etc.

These observations support the following conclusions:

1. FBSR tends to volatilize more of a radwaste’s semi-volatile components than does rotary kiln calcination.

2. FBSR’s lessened NO\(_x\) production comes at the price of producing much more of such reduced nitrogenous species as ammonia and hydrogen cyanide – any kind of calciner is going to need subsequent offgas treatment!

3. There little evidence that the “sodalite-like” cage minerals purported to immobilize anions such as chloride actually formed.

FBSR product characteristics: The following is based upon analyses of samples of what was in the two drums into which filter fines and bed products were dumped throughout the duration of the test.

- Ten-minute exposure of either powder to 100-fold as much 90°C water solubilized only a small fraction of the sodium – about 20% of that in the fines fraction, about 4% of that in bed product. This suggests that FBSR does indeed “mineralize” most of the sodium.

- The primary cation present in water leachates was sodium balanced by an equivalent amount of (in order of concentration) aluminate, carbonate (in fines, not bed), phosphate, sulfate, chloride, silicate, and fluoride ions.

- The bulk density of the filter fines product fraction was about 0.35 g/cc - that of the bed product, ~ 0.8 g/cc.

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6 The reasons for this are 1) fluidized bed reactors require higher gas flow rates; 2) the temperature required to make “water gas” are two hundred degrees higher than is required to efficiently sugar calcine radwaste; and 3) the vapor pressure of a molten metal is generally greater than that of its oxide.

7 The bulk density of a powder is not an absolute number because it depends upon its degree of consolidation (settling) before its volume is measured. The figures given in this paper were...
Several intrinsically volatile components of the SBW simulant – rhenium (technetium surrogate), cesium, chloride, sulfate, and phosphate – were present at much higher (several times as high) concentrations in the filter fines product fraction than in the bed product.

- The sum of all of sulfur-bearing species (sulfate, sulfite, and sulfide) found in both product fractions (plus the scrub liquor) accounted for less than one-third of the sulfate-sulfur fed to the reactor.
- The loss-on-ignition (primarily elemental carbon) of the final bed product composite was ~4.5% vs ~15 wt% in the filter fines drum.
- There was under 1 ppm of either ammonium or cyanide ion in either product.
- Hot water would dissolve the same amount of chloride from either product fraction as would high temperature fusions performed with NaOH or Na$_2$CO$_3$.

The overall degree of “volume reduction” achieved by “reforming” this SBW was not very impressive. For example, if we assume that …

1) a total of 385 grams of mineralized product is produced per liter of SBW
2) the mass-wise proportions of bed and fines products is 40:60
3) “Bed” is 5 wt% carbon &” fines” is 15% carbon
4) the bulk density of these fractions are 0.8 and 0.35 g/cc

A reasonable estimate of the volume of calcine generated from one liter of SBW would be …

$$((0.6\times385)/0.85)/0.35 + ((0.4\times385/0.95)/0.8 = 979 \text{ cm}^3$$

To a “grout” chemist, both product fractions were excellent from a purely chemical point of view and rather poor from a physical standpoint. “Good” because a nepheline-like mineral assemblage is intrinsically compatible with silicate-based cements. “Poor” because their low bulk densities and high BET surface areas causes them to exhibit high “water demand” (fines more so than bed). In practical terms, this means that a large amount of liquid is required to produce a grout that would flow well enough to readily fill a mold (waste canister). Since the total pore volume of fully-cured grout (concrete) generally approximates that of the water in the original formulation, this in turn, means that high water demand translates to a physically weak, porous, concrete. It also translates to low waste loading, both weight and volume-wise.

Due to time (and funding) constraints, only four fundamentally different types of grout were investigated and the total number of specimens produced was twenty-one. The waste simulant in these specimens generally consisted of a 50:50 weight-wise mix of bed and filter fines.

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obtained by dumping powder into a tared 10 cc glass graduated cylinder, tapping it for about 30 seconds, and then measuring its mass and volume. That much tapping typically reduces the volume of a dumped “fines” sample by about 50%
Similarly, the weight-wise percentage waste loading was also usually 50% (i.e., the mass of dry cementitious agent(s) equaled that of the calcine).

Etc., etc

A comparison of the observations that others made during this demonstration (also see Soelberg et al, 2004) with how THOR’s reports characterized it (see THOR no date) differ in many ways, the most important of which (to me anyway) is that THOR doesn’t bother to mention that only about one third of the waste surrogate’s primary ash forming constituents (sodium, aluminum, etc.) ended up in its much ballyhooed mineralized “grapenuts-like” product – the majority ended up as fines. They also don’t reveal that much of the surrogate SBW’s intrinsically volatile stuff (e.g., rhenium ($^{99}$Tc surrogate), chlorine, and sulfur) didn’t end up in either solid product – such things were mostly converted to gases, not sequestered within durable “cage minerals” as THOR’s DOE-Complex “helpers” often suggested. More importantly (to me anyway), the reports written by the national laboratory personnel that chose to “help” THOR didn’t point those things out either.

To date (4April2019), the roughly one billion dollars subsequently spent by INL’s clean-up contractors on its steam reformer hasn’t yet succeeded in converting any of its remaining SBW to either a “carbonate” or “mineralized” product. The problem seems to be the same one that plagued us during the “demonstrations” performed at INEEL’s STAR center almost two decades ago, fluidized bed agglomeration and “bark” formation. The chunky-stuff accumulations holding things up are probably comprised of the DMR’s fluidized bed particles glued together with waste surrogate-derived sodium/potassium carbonate. The much higher temperatures (~700°C) required to denitrade such waste with THOR’s proprietary solid reductants rather than with a water soluble reductant (~500°C) are responsible for this. With
something like sugar, the reductant is intimately mixed with what it’s to reduce (the liquid waste’s nitrate ions), not in an entirely separate phase, and therefore can completely react at temperatures well below those likely to melt/fuse the product.

APPENDIX XII describes one of the ways used to “sell” steam reforming to DOE’s stakeholders.

APPENDIX XV  Another solution to pollution

There’s currently a tremendous amount of handwringing going on about how plastic pollution is destroying our environment (especially the oceans) and we’re not really doing anything about it.

Let’s look at this “terribly difficult problem” the way that a chemist, engineer, or governmental decision maker should.

Total world plastic production is currently about 380 million tonnes per year, approximately one tenth of which (~40 million tonnes) is the relatively tough-to-burn chlorinated plastics - mostly polyvinyl chloride (PVC) [https://en.wikipedia.org/wiki/Polyvinyl_chloride]

In 1975/1976 the Canadian government implemented a large scale chlorinated hydrocarbon (including PVC plastic) incineration demonstration at the St Lawrence Cement Co in Missaugua, Ontario (“Burning Waste Chlorinated Hydrocarbons in a Cement Kiln”, a GOOGLABLE 1978 EPA report]). Those materials contained up to 46wt% chlorine. They were destroyed with >99.98% efficiency and no high molecular wt. chlorocarbons (e.g. dioxins) were detected in the off gas. As expected the amount of kiln dust produced – mostly a mix of sodium and potassium chloride salts often used as fertilizer – increased in stoichiometric proportion to the amount of chlorine fed to the kiln. Chlorine fed was up 0.8wt% of the clinker produced. Burning that waste reduced the amount of fossil fuels required to make the cement clinker and improved its quality (less alkali).
Global cement production is now about 4 billion tonnes [https://en.wikipedia.org/wiki/Cement]. A typical Portland cement is about 62 wt% CaO (molecular wt (MW)=56 g/mole) meaning that the limestone calcined to produce it contained about 1.95 billion tonnes \[4 \times 10^9 \times 0.62 \times 44/56\] of carbon dioxide (MW=44 g/mole) all of which was dumped into the atmosphere. A typical large, wet process rotary cement kiln, fitted with drying-zone heat exchangers, produces about 680 tonnes of clinker per day and burns 0.25–0.30 tonnes of coal fuel per tonne clinker to do so.

Assuming the highest carbon, highest heating value coal (anthracite essentially 100% C, 33 MJ/kg heating value) the amount of coal burned to satisfy the world’s cement demand would be \(\sim 1.0\) billion tonnes \[0.25 \times 4 \times 10^9\] the combustion of which would generate 3.67 \((1.0 \times 44/12)\) billion tonnes of CO2 which is also dumped into the atmosphere.

Most plastics exhibit about the same heating value as crude oil (~42 MJ/kg) meaning that if 100% of the plastics made/consumed per year were to be burned in the world’s cement kilns rather than dumped into the oceans or landfills, the amount of coal burned to make cement would be reduced by nearly 50% \(0.38 \times 42/33 = 0.485\) billion tonnes. Because plastic has a somewhat higher heating value per carbon atom as coal, that substitution would also reduce the total amount of CO2 generated/dumped per tonne of cement.

What’s so tough about deciding how we should address plastic pollution other than our all-too “human nature”?

**Appendix XVI**  
Statement from someone brought in (too late) to try to straighten-out INEL’s Naval fuel reprocessing boondoggle (Names deleted)

“I don't remember or know what may or may not have been promised to the Admirals. I also do not contend that the bureaucracy (both DOE and predecessors and the Chem Plant management) did not promote unknown or unproven
technologies as being turnkey. The new FDP plant was built and designed for reasons that cannot be fully revealed because of classification aspects. That is why "even I can't reveal that our system didn't work as we had promised". The original Chem Plant developers, the secretive XXXXX XXXXXX and XXX XXXXX did not appreciate that the old efficient E-cell process could not be translated directly to the FDP. Their early process didn't work. At the time, it was widely perceived in the Complex that we had another Rocky Flats fiasco. That was when I was brought in to do address the problems. Being totally ignorant of all the classified stuff, I was not biased to any existing chemistry and started from scratch to develop it for the specific fuel. Yes, we did have to shoe horn some of it into the existing equipment. If I could reveal classified stuff to you, I could explain clearly to you how well the process actually worked in the end, though differently than may have originally been promised. And, as I've explained, our advanced process that may be implemented is an order of magnitude improved. Don't know why that was not looked at originally. This Zircex process was developed in the 1960s for naval fuels. This was, of course, subsequent to building the E-Cell process that started up in 1953. I guess that the new Fluorinel plant design was just doing more of what they had experience with. We now recognize the great benefits of Zircex.

One contributor to the bloating costs that changed from the old E-cell days and after we started the FDP process was the rapidly exploding regulatory, QA, safety and security organizations that increased our staff and operating budget greatly. Also, as previously mentioned, the HLW quantities and management costs were substantial. Yes, this was a factor in the shutdown process. However, criticism of the technical aspects of the process, itself, other than some deficiencies in the original plant design, for example, a single PTV, though you may perceive as bad, is not warranted. Again, if we could have a sit down full discussion of the classified aspects, you would understand.

Your general criticism of the government bureaucracy is valid. Attempting to dredge up a four decades ago decision, IN ABSENCE OF SPECIFIC CLASSIFIED FACTS, is treading on thin ice. It leads to incorrect suppositions. Better to focus on more recent and currently on-going fiascos such as the IWTU (misnomer, because the original plan to yank out the steam reforming vessels and install hipping for calcine, thus "Integrated", could not have been physically
accomplished). And, of course, the Hanford Vit Plant and process makes IWTU look like kindergarten. Yes, goal line shifting is a perfected art!”

APPENDIX XVII  Best-yet explanation of how “renewables » are being subsidized  (Rogers 2019)

The solar energy industry is telling its pals in Congress that it is willing to lose most of its subsidies. The current subsidy for solar is 30% of the construction cost. To that subsidy, an additional 10% subsidy is available due to special fast depreciation for solar energy plants. The 30% subsidy is scheduled to ramp down to 10% by 2022 and thereafter remain at 10%. This is not a consequence of declining costs of solar that makes the industry no longer in need of such a large subsidy. Solar electricity is a mature industry, and cost declines are moderate. The real reason the solar people are happy with a lower subsidy is that the 30% investment tax credit (ITC) is not their most important subsidy. The real subsidy is more complicated and better hidden. The real subsidy is rooted in renewable portfolio requirements in about 30 states. These states require that a certain percentage of electricity come from renewable sources. The quota ramps over time. For example it might ramp from 20% now to 50% by 2030. These quotas create a chain of events that guarantee solar and wind energy a market for years to come with a guaranteed profit. If that is not enough, the industry is trying to freeze the quotas into state constitutions so as to make it difficult for the electricity consumers to get out of the trap that has been set for them.

Renewable energy has been defined in an illogical way so as to favor solar and wind. The ostensible motive for increasing renewable energy is to lower carbon dioxide (CO₂) emissions and thus avoid a supposed global warming catastrophe. But hydro and nuclear are prohibited from being used to meet the renewable energy quota, even though they don’t emit CO₂.

Electricity is responsible for 28% of U.S. CO₂ emissions. The rest is from transportation, heating, and industrial processes. Yet the emphasis on reducing CO₂ is focused on the electricity sector. The U.S. is responsible for 14% of world CO₂ emissions, and our electricity generation creates less than 4% of world
emissions. All the effort being put into U.S. renewable electricity will have no important effect on global warming, assuming that global warming is even real. The real source of CO₂ emissions is China and India among others.

I will explain how renewable energy quotas subsidize solar. The argument for wind is similar but different in various details. To see how big the subsidy is, I will compare an imaginary, unsubsidized solar electricity business with the existing situation, propped up by subsidies and quotas.

Our imaginary unsubsidized solar business is going to sell electricity to various utilities that its electricity can reach via the transmission networks that are open to companies exchanging electricity.

Solar electricity is erratic electricity. You get it during the day, when the sun is not obscured by clouds. The utilities that deliver electricity must supply electricity in a predictable and non-erratic manner. Why would any utility even want erratic electricity? The answer is that the utility can use its existing plants to compensate for the erratic nature of the solar. The value to the utility of the solar electricity is the value of the fuel saved in its existing plants when solar electricity is actually flowing. Solar can't replace existing plants because sometimes it's not there, particularly in the early evening, when electricity demand often peaks. On the negative side, solar lowers the utilization of its existing plants and stresses them more, increasing the cost of electricity from existing plants.

To summarize a complicated story, solar electricity is worth about $20 per megawatt-hour to a typical utility.

Our imaginary company with a speculative market and no guarantees would need an 8% return over a 10-year period to justify the investment. Under these conditions, it is not remotely possible to sell solar electricity for $20 and get the 8% return appropriate to this speculative business. The company would have to get about $100 per megawatt-hour to stay in business. One hundred dollars per megawatt-hour is the true price of solar electricity in a free market.

But suppose the solar company has a 25-year contract with a utility guaranteeing a market and price. Then our not so imaginary company could be financed with a rate of return of 4.5% over 25 years. Under these conditions, the company could
prosper by selling electricity for $37 per megawatt-hour. Take it one step farther and assume we have the full 30% ITC, which, in combination with rapid depreciation, is a 40% subsidy. Under those conditions, the company could sell electricity for $22 per megawatt-hour. That $22 per megawatt-hour is in line with the lowest-cost solar agreements being signed at the present time. The subsidy is $100 - $22, or 78%. Take it one step farther and consider when the ITC ramps down to 10%. The subsidy from the ITC and the rapid depreciation will then be 20%. In this case, the electricity can be sold for $30 per megawatt-hour and the company will still get its return.

Because utilities are forced to search out renewable electricity due to the quota, they have to provide terms that will cause the installations to be built. Those terms are driven by long-term interest rates and the cost of building the solar installations. When, and if, the ITC is reduced from 30% to 10%, we can expect the best power purchase agreements to rise from $22 to $30 per megawatt-hour, or a bit less if the industry lowers its costs. The profits of the industry will remain the same. The renewable portfolio quotas protect the business. The payer of the subsidy shifts from taxpayers to electricity consumers when the direct subsidies are reduced.

If the quotas were repealed, the utilities would have little incentive to offer long-term contracts to solar energy producers. The utilities might be willing to pay $20 for the electricity, but without the long-term contracts, the required rate of return needed for a viable business would be much higher, and that would be unobtainable with the $20 amount the utilities would be willing to pay. Even with the 40% existing federal subsidy, the solar producers would need about $60 per megawatt-hour to get an 8% return over 10 years.

What this comes down to is that if you guarantee a market and price for 25 years, that is of great value to the company receiving it. You have taken away most of the risk, and risk requires higher returns. A company with such guarantees is more like a government bond than a normal enterprise.

The proselytizers for renewable energy have cleverly created a good business by convincing states to set quotas for renewable energy. Because there is a quota, the utilities will sign contracts that will result in providing the needed supply. The
quotas are justified on the grounds of saving the Earth from global warming, but even if global warming is a real danger, the problem is in Asia, not in the U.S. electricity sector. By banning hydro and nuclear on spurious grounds, the wind and solar industry has fended off the competition for CO2-free electricity.

Experts like James Hansen and Michael Shellenberger, that really, really believe in global warming, are loudly saying the solution is nuclear, not wind or solar.

It's time to get rid of the subsidies and quotas and put these scammers out of business.APPENDIX XVII Best-yet explanation of how “renewables » are being subsidized (Rogers 2019)

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**APPENDIX XVIII Some educated guesses about US Naval reactor fuel**

The demise of DOE/INEL’s Naval fuel reprocessing project marked the end of its ”Chem Plant’s” constructive era – its next three decades were devoted to “decommissioning” and “waste management”.

The reason for that project’s fate was that its newly built fuel dissolution system did not function nearly as quickly or efficiently as “promised” resulting in that project’s cost/benefit ratio rising to a point deemed unacceptable to its decision makers in light of the fact that the USSR’s recent collapse had lowered the value of such « second hand » fissile.

Because the “Chem Plant” had previously successfully reprocessed a good deal of conventional-type PWR fuel, it’s highly likely that its new dissolution facility’s issues were due to differences between such fuels not considered by its designers.
While virtually everything about the Navy’s reactor fuels remains a closely guarded secret, enough is known about them to hazard some educated guesses about what those technical issues might have been.

To begin with, what isn’t a secret is that Admiral Rickover decided that his reactors would be PWRs fueled with highly enriched uranium imbedded in one way or another in zirconium.

Conventional PWR reactor fuel consists of roughly 8 mm diameter 2 cm long cylindrical pellets of a brittle UO$_2$ ceramic tightly encased within ~ 3 meter long, thin-walled zirconium tubes. The navy’s fuel is different because its needs are different – its reactors must be much more compact and their fuel must last much longer; e.g., 33 vs just 2-3 years. It also differs in that the US military isn’t bound by the Nuclear Non-Proliferation Treaty’s rules and can spend as much money on fuel as it wishes, hence its use of HEU instead of low enriched uranium (LEU).

There’s been a good deal speculation about that fuel’s makeup largely driven by the fact that other countries’ naval reactors seem to operate perfectly well with LEU (<20%$^{235}\text{U}$- not « weapons grade ») uranium-based fuel.

The following speculations are based upon four reports GOOGLED up 8/22/19. One is a MS thesis from MIT (McCord 2014), one is an Russian report about an “advanced” fuel being developed for its PWRs (Fedik 2004), and two are US written/published reports having to do with proposals to fuel US Naval reactors with LEU (Ma & Hipple 2001 & Haghighat 2015)

Current naval fuel, while classified, is widely believed to be a ‘cermet’ design, meaning that it is a combined metal-ceramic dispersion material. In this case the metal is zirconium and the ceramic is almost surely uranium dioxide, UO$_2$. The fuel pellets are likely manufactured by mixing powdered zirconium and tiny somewhat porous UO$_2$ particles together, hot pressing them to form cylindrical pellets, which are then incased within zirconium (or Zircalloy) tubes. I also suspect that those tubes are plated (or alloyed) with the mysterious metal about which no one could speak in order to render them more corrosion resistant.

Here are some facts (?) gleaned from the aforementioned references along with some ball park guesses based upon them about what they might mean.
A Los Angeles class nuclear submarine possesses a 130 MWt reactor that supposedly runs for an average of about 6 months per year during which time its averaged output is about 25% of its maximum rating. Its reactor’s initial fuel loading is also supposed to last for its entire lifetime, 33 years.

Some of Russia’s icebreakers are similarly powered (135 MWt) with PWRs about which more details have been revealed. One fact in particular is that the “smear density” (grams of uranium/cc fuel) of their fuel is 4.5 g/cc.

Total energy generated by LA class sub’s fuel = \(135 \times 10^6 \times 3600 \text{ s/hr} \times 24 \text{ hr/d} \times 365 \text{ d/yr} \times 6/12 \times 0.25 = 1.69 \times 10^{16} \text{ J}\)

Which requires the fissioning of \(5.28 \times 10^26 \times \frac{1.69 \times 10^{16}}{3.2 \times 10^{11}}\) atoms of fissile \(^{235}\text{U}\)

Which is 877 \([5.28 \times 10^26/6.023 \times 10^23]\) gram moles or 206 kg of \(^{235}\text{U}\) “burned” over 33 years

(Incidentally, the Russians also discovered/revealed that adding 3% of an especially special element rendered their fuel’s Zr cladding more durable)

The Russians’ UO\(_2\)/zirconium CERMET fuel pellets possess a diameter of \(~0.8\) cm and consist of \(~10\)% porous UO\(_2\) granules embedded in zirconium metal. The volumetric ratio of ceramic to metal within them is about 3:1 \((75\% \text{ UO}_2)\) and they are contained within \(~0.5\) mm thick walled zirconium tubes with an “air” gap between them of about 0.1 mm\(^{518}\). They are also expected to achieve 120 MW day/kg U burn up. Since the theoretical density of pure UO\(_2\) is 10.97 g/cc, the density of that within the fuel pellets must be 10.97\(*0.9\) or 9.873 g/cc

\(^{518}\) The purpose of using deliberately porous UO\(_2\) and an “air gap” is to provide room for the fission products generated when some of the fissile fissions. That FP would otherwise over-stress the cladding tube.
Since the density of zirconium is 6.49 g/cc & it represents 25 vol% of the pellet, that pellet’s density must be \[9.873 \times 0.75 + 0.25 \times 6.49\] = 9.027 g/cc

The smear density of the uranium in it would be 5.959 g/cc \[0.75 \times 9.027 \times 235/(235+2 \times 16)\]

Pellet end-on area = 0.5027 cm^2 \[(0.8/2)^2 \times 3.1416\]

End-on area of the fuel «pin” = 0.6648 cm^2 \[(0.4+0.06)^2 \times 3.1416\]

Fuel assembly uranium smear density = 4.506 g/cc \[5.959 \times 0.5027/0.6648\] (which figure agrees with the Russian paper’s claim)

120MWd/kg = 1.037E+13 \[120 \times 6 \times 3600 \times 24\] J/kg

100% fission/kg = \((1000/235)\times 6.023E+23/3.2E-11\) = 8.2015E+13 J/kg

Fraction \(^{235}\text{U}\) burned = \(5.7024E+12 / 8.20153E+13\) = 0.126

total U in core = 206 kg burned/0.126 f burned=1630kg

core volume sans water etc = kg tot U/ fuel U smear density = 1630/4.506 = 362 liters

If fuel assembly pitch-to-diameter ratio is the same as that of a 17 by 17 PWR’s (12.6 to 9.5 mm) then the volume of the core’s hot region must be about 362*(12.6/9.5)^2 or 637 liters (if a right circular cylinder it’d be just over a yard (three feet) both high & wide)

APPENDIX XIX  A comparison of different approaches to providing public transportation

Whenever I feel myself becoming too complacent about how great the USA is relative to foreign countries, I do a bit more GOOGLING*. For instance, today (8/25/2019), I learned that …

Spain’s 25 year-old 100% electrified, high-speed, passenger trains run at speeds of up to 190 miles/hr and enable fast connection between Spain’s. For example, there are 17 trains/day to/ from Madrid/Seville (about 240 miles) that take about 2
hours, 21 minutes each & a 2nd class seat ticket on them costs ~$30

AVE’s (Spain’s) passenger trains feature:

- Air conditioning
- Audio system
- Liquor Bar
- Child supervision
- Children's play area
- Coffee bar
- Disabled facilities
- Newspapers/magazines
- Power sockets
- Restaurant/bistro
- Video screens

…and its train-seating experts don’t do things like trying to shoehorn 187 people into something the size of a Boeing 737.

Here’s a review by someone (a« foreigner ») who’s obviously become “spoiled” by the EU’s rail-based people transport system

"Overall the trip is satisfying. However, the price is a bit high."

A bit more GOOGLING revealed that…

Amtrak’s Philadelphia to Pittsburg (about 260 miles, one train/day with 12 intermediate stops service) train takes 7 hours and 25 minutes (~35 miles/hr) to do so & a ticket costs $68 (about 26 US cents/mile)
https://www.cheapoair.com indicated that a next day’s one-way airplane ticket cost between those cities ranges from $210 to $540 - $0.81 to $2.08 per mile. ( « gas mileage » = 70-100 miles/gallon/seat)

At the other end of the public travel-cost spectrum, a typical Chinese “slow train” route of about 220 miles, features 28 stops, and moves at an average speed of ~43 miles/hr. However, its tickets cost its riders only about 1.5 US cents per mile (21 Y/350 km).

Non public transportation: The USA’s most popular vehicle, Ford’s F100 pickup, apparently gets a real-world average of about 12 mpg & Pennsylvania’s current gas price averages ~$2.61/gallon. Those figures plus an assumption that an average American would average 60 miles/hr between Phildelphia & Pittsburg, indicate that his/her trip would take 4hrs and 20 minutes and the necessary gas would cost $55.56 (21 cents/mile).

*The American Dialect Society considered GOOGLING to be its "most useful word of 2002." It certainly deserves that appellation.

APPENDIX XX worked-out water/CO₂ equilibria examples

(see also http://lawr.ucdavis.edu/classes/ssc102/section5.pdf )

This TABLE lists several especially relevant water pH buffering reactions
two others include

Ksp calcite: \( \text{CaCO}_3 \rightarrow \text{Ca}^{++} + \text{CO}_3^{=} \) dissolution of calcite= 3.3E-9

(Ksp = solubility product = concentration of \( \text{Ca}^* \) conc. carbonate)

Kw \( \text{H}_2\text{O} \rightarrow \text{H}^+ + \text{OH}^- \) Dissociation of water \( 10^{-14} \)

The table’s dissolved species concentrations are in units of gram moles per liter – the gaseous specie (\( \text{CO}_2 \)) is in standard atmospheres (or BARs)

The equilibrium constants (Ks) represent the ratio of the product of product species (right side)/ reactant species (left side) e.g. for rxn. no.2, \( K = (\text{H}^+)(\text{HCO}_3^-)/\text{H}_2\text{CO}_3 \)

These K’s are for distilled water at 25°C and will vary with T & salt concentrations (‘ionic strengths’)

The activity (effective concentration) of water in almost any aqueous solution is 1.00

Examples:

#1 if atmospheric P = 1 BAR (sea level) & that the air contains 400 ppmv \( \text{CO}_2 \) what’s \( \text{H}_2\text{CO}_3^- \)?

<table>
<thead>
<tr>
<th>Reaction No.</th>
<th>Equilibrium Reaction</th>
<th>Log K⁰</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( \text{CO}_2\text{(g)} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3^- )</td>
<td>-1.46</td>
</tr>
<tr>
<td>2.</td>
<td>( \text{H}_2\text{CO}_3^- \cdot \text{H}^+ + \text{HCO}_3^- )</td>
<td>-6.36</td>
</tr>
<tr>
<td>3.</td>
<td>( \text{HCO}_3^- \cdot \text{H}^+ + \text{CO}_3^{=} )</td>
<td>-10.33</td>
</tr>
<tr>
<td>4.</td>
<td>( \text{CO}_2\text{(g)} + \text{H}_2\text{O} \cdot \text{H}^+ + \text{HCO}_3^- )</td>
<td>-7.82</td>
</tr>
<tr>
<td>5.</td>
<td>( \text{CO}_2\text{(g)} + \text{H}_2\text{O} \cdot 2\text{H}^+ + \text{CO}_3^{=} )</td>
<td>-18.15</td>
</tr>
</tbody>
</table>
since to a first approximation all gases occupy the same space/mole (~22.4 liters at one atmospheric pressure & 0 °C) this example’s partial pCO₂ = 400E-6 atm, so H₂CO₃ ° = 10⁻¹.₄₆* 400E-6 = 1.38E-5 molar

What’s the pH of distilled water in contact with it

H₂CO₃ ° partially dissociates to form one H⁺ cation plus one HCO₃⁻ anion

so, H⁺ = (H₂CO₃⁻) = - (1.38e-5*10^-6.36)^[0.5] = 2.45E-6

(it’s distilled water therefore no other ions)

pH = negative log H⁺ = -log10(2.25E-6) = 5.61

An important reaction in most soils and waters is the precipitation of calcium carbonate because calcium is the most common carbonate precipitating species (calcium bicarbonate is freely soluble as are sodium/potassium carbonate/bicarbonates)

Ksp (solubility product) in low-salt water at 25°C is 3.3×10⁻⁹ = [Ca⁺²] *[CO₃⁻²]

#2 What’s the pH of water in equilibrium with Ca carbonate & the atmosphere at 25°C?

from what we’ve already done above we know that the amount of H₂CO₃ ° is 1.38E-5 molar

we also know that H⁺ + 2*Ca⁺² (equivalents of cations) = OH⁻ + H₂CO₃⁻ + 2*CO₃⁻² (equivalents of anions)

to solve this turkey we must express everything in terms of what we know i.e., H₂CO₃ °, the constants & what we’re looking for; i.e., H⁺

i.e., H⁺2*Ca⁺² = OH⁻+HCO₃⁻+2*CO₃⁻²

when you’ve done so, you end up with a quadratic equation in terms of H⁺

H⁺ + 2*H⁺²*K5/k2/k3/ H₂CO₃ ° = Kw/ H⁺ + (H₂CO₃ °)*k2/ H⁺ + 2*k2*K3* H₂CO₃ °/H⁺²

It can be solved elegantly or by simply substituting inputted guesses for H⁺ into both sides of the equation until you get a charge balance (that’s the way I do it
because I’m old, have forgotten how to solve quadratic questions, & now have EXCEL to do that sort of scutwork)

The result I got (you might want to check it) is an $H^+$ concentration of 6.4E-9 molar which corresponds to a pH of 8.19.

It’s no accident that this pH is pretty close to what we used to see in the oceans (their pH is currently about 0.1 pH unit lower)

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