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Fast Neutron Reactors (FNRs) for Mitigation of Climate Change (Part 1, Nuclear Fuel Issues)

C. St. L. Rhodes
Xylene Power Ltd., Sharon, Ontario, Canada
CSLRhodes@gmail.com. **Charles.Rhodes@xylenepower.com**

Abstract:
It is shown that fossil CO2 induced climate change is much more serious than most people are aware. Preventing further fossil CO2 induced climate change requires halting combustion of fossil fuels and replacing fossil fuel sourced power with a mix of renewable power and nuclear power. Renewable power is inherently not dependable. Nuclear power from fission of U-235 is not sustainable. The only source of sufficient dependable and sustainable power for full displacement of fossil fuels is fuel sustainable Fast Neutron Reactors (FNRs) fueled by U-238. These reactors require core fuel containing TRU (Np, Pu, Am, Cm …). There is a world shortage of TRU for power generation. TRU can be extracted from used CANDU fuel, from used FNR fuel or made with Intense Neutron Generators (INGs). Absent commencement of TRU production now the world will run out or economic dependable clean (non-fossil) power as the U-235 resource is depleted. The government of Canada is presently blocking TRU production.

1. Summary:

- Combustion of fossil fuels raises the atmospheric CO2 concentration which causes a prompt rise in dry bulb temperature and, due to ocean heat capacity, a delayed rise in wet bulb temperature;
- The rise in wet bulb temperature reduces human body cooling capacity which increases demand for air conditioning and forces human migration away from the tropics;
- Preventing further increases in the atmospheric CO2 concentration requires halting world combustion of fossil fuels;
- Displacing the 20,000 GWt of thermal power presently provided by combustion of fossil fuels requires an equal amount of clean thermal power;
- Thermal neutron (water cooled) reactors that rely on U-235 cannot sustainably displace fossil fuels due to the limited economic natural uranium resource;
- Sustained fossil fuel displacement requires Fast Neutron Reactors (FNRs) that fast fission TRU while converting abundant fertile U-238 into even more new TRU;
- Stopping CO2 emission by 2070 requires immediate construction of CANDU reactors, FNRs and Intense Neutron Generators (INGs) to make sufficient TRU for future FNR fleet expansion.

This paper addresses **FNR fuel measures** necessary to enable sustained full displacement of fossil fuels by nuclear energy. A companion paper addresses FNR hardware issues.

2. Introduction:

Our society harvests natural sources of energy for the benefit of mankind. A country's average energy consumption per person is one indication of its average standard of living.

Since the dawn of the industrial revolution mankind has obtained energy when and where required by burning fossil hydrocarbons. Initially the combustion rate was small compared to the natural CO2 sequestration rate, so the net effect on the atmospheric CO2 concentration was negligible.

However, by 1957 the atmospheric CO2 concentration had risen from its historic value of 280 ppm to 315 ppm. Today, in 2024, the atmospheric CO2 concentration is about 422 ppm and is rising at about 2.5 ppm / year.

On November 24, 1996 a US interplanetary spacecraft named the Mars Global Surveyor, while on its way to Mars, recorded the infrared emission spectrum shown by the black line on Figure 1. The horizontal axis is: (wave number) = (photon frequency) / (speed of light).

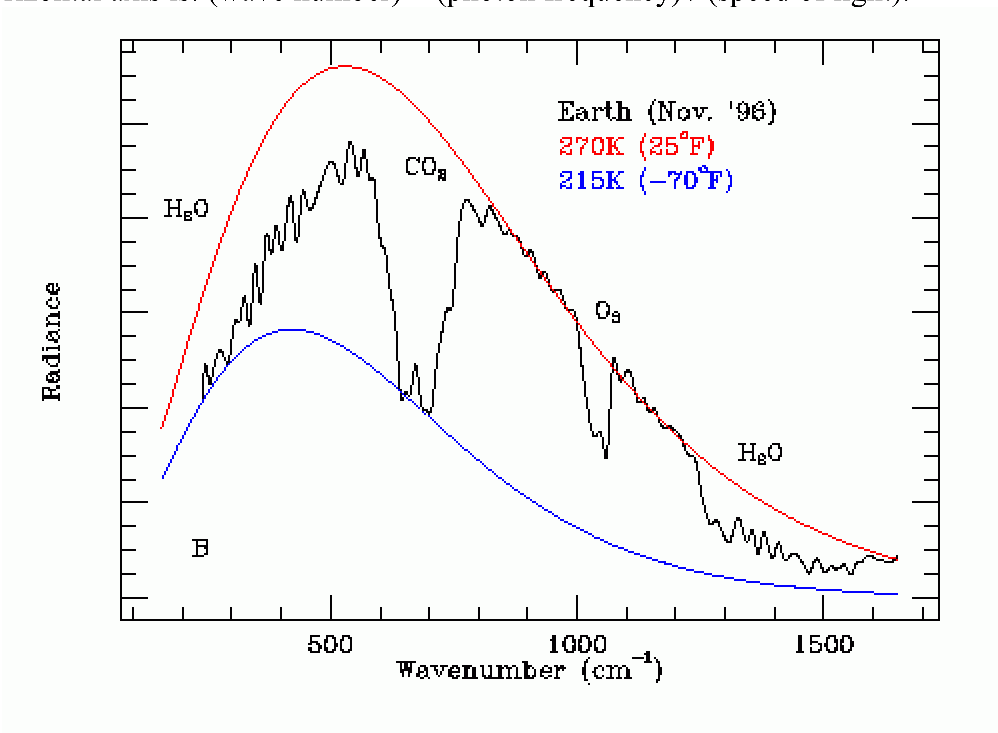

Figure 1

The area under the black line is Earth's total IR Radiant Emission power over the Pacific Ocean. Note that the effect of atmospheric CO2 and other green house gases is to reduce the area under the black line. As the atmospheric concentration of greenhouse gases increases the area under the black line and hence the total IR emission decrease.

The net radiant heat absorption by planet Earth is given by:
[Earth's Net Radiant Heat Absorption] = [Solar Radiation Absorption] – [IR Radiation Emission]

Prior to mankind's large-scale combustion of fossil fuels Earth's average surface temperature was stable, indicating that historically:
[Earth's Net Radiant Heat Absorption] = 0.

Over the last century, due to melting of polar, glacier and seasonal ice Earth's average solar reflectivity has decreased causing the the average value of:
[Solar Radiation Absorption]
to increase.

During the same period, due to combustion of fossil fuels, the atmospheric greenhouse gas concentration has increased causing the average value of:
[IR Radiation Emission]
to decrease.

Hence today the
[Earth's Net Radiant Heat Absorption]
has positive components due to changes in both
[Solar Radiation Absorption] and [IR Radiation Emission].

Figure 2 Earth as photographed 1n 1972 from Apollo 17.

This net heat absorption will continue until the ocean temperature rises enough to restore the equality:
[Solar Radiation Absorption] – [IR Radiation Emission] = 0

The problem is that due to melting of circumpolar ice, both terms of this equation have to increase a long way to restore the difference to zero. To appreciate the scope of the required increase in atmospheric temperature examine Figure 2 which is a 1972 visible light photograph of planet Earth from outer space.

The positive value of:
[Earth's Net Radiant Heat Absorption]
is causing a myriad of phenomena including a prompt rise in average dry bulb temperature over dry land and a delayed long-term rise in average wet bulb temperature over the ocean. This delay is due to the heat capacity of the oceans.

Persons who properly understand astrophysical energy transfer have been raising the alarm about this matter for over 50 years. Most people do not understand the scope and duration of this matter because they lack even a high school understanding of the relevant physics.

In Canada, in 2023, the increased average dry bulb temperature caused record wildfire damage, ice road destruction, permafrost melting and sea level rise. The rise in wet bulb temperature caused by the increase in ocean surface temperature and associated atmospheric water vapor content is turning otherwise rare violent ocean storms into routine events. These climatic change effects have severe negative implications for fishing, farming, forestry and agriculture. The climate change consequences in the USA, Europe and elsewhere are comparable.

As the wet bulb temperature rises and approaches the human body temperature (38 deg C) the human body can no longer cool itself by evaporation of perspiration. For this reason humans cannot function effectively at wet bulb temperatures exceeding about 32 degrees C.

The increase in average wet bulb temperature is causing an increased demand for electric air conditioning and large-scale human migration away from tropical countries,

Even if we could stop all injection of greenhouse gases into the atmosphere tomorrow, the rise in wet bulb temperature would still continue for decades into the future due to the response delay caused by ocean heat capacity. Hence the Global Warming problem is considerably worse than has been conveyed to the public.

The demonstrated unwillingness of mankind and its leaders to collectively face this climate change challenge is now a near-term threat to mankind's existence as a species.

The rising atmospheric GHG concentration is mainly due to extraction and combustion of fossil fuels. If fossil fuel consumption is permitted to continue, the resulting rise in both dry and wet bulb temperatures will eventually drive most large land animal species into extinction. There is no fix for this problem other than leaving fossil carbon in the ground. The sooner that everyone grasps that simple concept, the better.

3. Earth's Geologic History

The concept of CO_2 Capture and Storage (CCS), as advocated by many fossil fuel companies, is a total hoax as it does nothing to reduce the CO_2 emissions long-term.

Isotopic analysis of ocean floor drill cores has shown that during the several hundred million year period prior to the existence of mankind the atmospheric CO_2 concentration was usually nearly stable in the range 220 ppm to 300 ppm. However, there were a few relatively short transient high spikes in the atmospheric CO_2 concentration such as in the PETM. Those spikes coincided with high temperature global extinctions of large land animals. The time frame for natural recovery from those transient high CO_2 concentration spikes was 10,000 to 200,000 years, depending on the sources of the CO_2 spikes.

The lesson from geologic history is that, if by combustion of fossil fuels mankind triggers another such geologic atmospheric CO_2 spike, mankind will be thermally driven into extinction long before natural processes return Earth's atmosphere to its stable CO_2 concentration range.

4. Interruptible and Dependable Electricity Generation:

There are two major categories of clean (non-fossil) electricity, interruptible electricity from renewable sources such as wind and solar electricity generation and dependable electricity from nuclear power plants. Practical experience around the world has demonstrated that typically the **maximum fraction of total electricity grid energy that can be economically supplied by renewable generation is about 25%.** Unless there are really exceptional hydro-electric energy storage resources, such as in Quebec and Norway, above that fraction the marginal cost of integration of renewable energy becomes prohibitive. In a clean electricity system the remaining 75% of the grid energy usually must be nuclear.

5. Political Response:

The recent knee jerk political response to climate change has been for governments to order more thermal neutron (water cooled) power reactors like those in use today. However, even a high school student can easily show that, due to the relative scarcity of economic natural uranium, thermal neutron reactors cannot sustainably displace fossil fuels. Their fuel cycle does not generate enough fissile material to offset the U-235 that they fission.

6. Political Corruption and Incompetence:

The era of major engineering decisions being made by uninformed politicians, who do not fully understand the long-term physical consequences of their decisions, must end. Global warming is a major public safety matter. It should be resolved by qualified professional engineers who fully understand the physics and the long-term consequences. The time for tolerance of incompetence and political corruption is over.

7. Engineering Response:

Supply of dependable clean power for sustained fossil fuel displacement requires large scale deployment of **fuel sustainable** Fast Neutron Reactors (FNRs) fueled by the abundant uranium isotope U-238, with the necessary start TRU being supplied by reprocessing of used nuclear fuel and by Intense Neutron Generators (INGs).

TRU (TRans Uranium actinides) are atoms with atomic numbers greater than 92. TRU forms when U-238 absorbs thermal neutrons. Owners of thermal neutron reactors often consider TRU to be long-lived nuclear fuel waste. In a FNR, the unique properties of TRU enable fuel sustainable operation and TRU inventory growth.

In the mid-1960s Atomic Energy of Canada Ltd (AECL) had two nascent clean power technologies. One was an Intense Neutron Generator (ING) . A ING is essentially a 1 GeV proton accelerator fitted with a flowing Pb-Bi eutectic target, a Be neutron multiplier, a heavy water neutron moderator and a surrounding sub critical blanket. By a process known as neutron spallation this apparatus produces about 25 useful thermal neutrons per incident 1 GeV proton and then further doubles its neutron flux by partial fission of accumulated TRU in the U-238 blanket.

ING technology, as developed by AECL during the early 1960s, is described in **ING Status Report July 1967 AECL-2750.**

The alternative AECL energy production technology was a simpler thermal neutron reactor, today known as CANDU, that requires as fuel the relatively rare uranium isotope U-235. During the late 1960s AECL believed that Canada had sufficient U-235 to last for centuries, so the more expensive ING technology was shelved.

Today, there are about 400 large thermal neutron reactors operating around the world and more than 10X that many are required to mitigate climate change. However, the economic natural uranium resource is insufficient to meet the life cycle U-235 requirements of both the present and contemplated new thermal neutron reactors. As a result the spot price of natural uranium has recently increased four-fold.

Hence, most of the new reactor fleet required to mitigate climate change must be composed of fuel sustainable FNRs. Some of these FNRs can be started using TRU extracted from used CANDU fuel. However, INGs are required for timely production of initial TRU for the remaining FNRs. The FNRs continuously fission TRU while converting yet more U-238 into TRU so, once started, FNR energy production can continue as long as there is U-238 feed stock, The isotope U-238 is 140X more abundant than the isotope U-235 so, from a practical perspective, INGs and FNRs fuelled by U-238 are fuel sustainable whereas thermal neutron reactors fueled by U-235 are not.

It is critical for present young people to grasp that if they fail to conserve TRU and to promptly deploy sufficient ING and FNR capacity they and their descendants will become victims of climate change. Sadly, young people can no longer rely on older people to give priority to future human welfare.

However, FNR deployment in Canada is entirely dependent on required changes in both Canadian federal nuclear legislation and provincial electricity legislation. Today it is up to younger engineers to do all necessary to effect these legislative changes.

A blunt reality today is that FNRs cannot be financed without a certain supply of suitable fuel, but production of suitable FNR fuel is presently being blocked by outdated and irrational government policies in both Canada and the USA.

Existing fossil fuel producers and their shareholders regard sustainable nuclear power as an existential threat to their future business and continue to do all in their power, including financial corruption of governments, to delay implementation of the legislation required for FNR and ING deployment.

One need look no further than the Trans Mountain oil pipeline to grasp the extent of this corruption in Canada. Between 2016 and 2024 the government of Canada committed over $30 billion of Canadian tax payers money to an oil export pipeline when that money should have been used for encouraging deployment of additional CANDU reactors, FNRs, INGs and related fuel technology.

The law of conservation of energy indicates that preventing a further rise in the atmospheric CO_2 concentration requires clean generation with a thermal and electrical output sufficient to displace the worldwide 20,000 GWt of thermal power that is presently being supplied by combustion of fossil fuels.

That displacement will require both maximum economic renewable energy generation and a fleet of
INGs and FNRs with a total equivalent thermal power output of about:
0.75 X 20,000 GWt = 15,000 X 1 GWt,
which could potentially provide a total electric power output of about:
15,000 X 300 MWe.

Deploying these INGs and FNRs will require a sustained industrial effort on a scale comparable to world ship building and passenger aircraft production.

For the circumpolar countries to sustainably and economically reduce their CO_2 emissions it is necessary for these countries to deploy **urban sited** fuel sustainable sodium cooled FNRs to provide both dependable electricity and low-grade heat to displace the fossil fuels that are presently used for water and space heating. This measure alone can potentially reduce the required overall reactor capacity by more than 2X.

At this time there is almost no public awareness that, as the economic supply of natural uranium dwindles, mankind's survival will depend on INGs, FNRs and related nuclear fuel reprocessing technology. **Failure to promptly deploy INGs and FNRs at a sufficient rate now is not a near term cost saving measure, it is a death sentence for our grandchildren. Decades are required for the TRU inventory to grow within the INGs and FNRs.**

Governments are currently being lured by false promises of CO_2 capture and storage (CCS). CCS is only a weak excuse for yet more fossil fuel production and consumption. However, pyrolysis of CH_4 in a nuclear reactor with carbon burial is a potential commercial source of hydrogen.

Preventing further increases in atmospheric CO_2 concentration also requires implementation of a retail electricity rate structure such that electricity, not a fossil fuel, is preferentially used whenever surplus clean electricity generation capacity is available. This measure requires adoption of distinct dependable and interruptible retail electricity rates that reflect actual electricity system costs. This measure would allow effective use of surplus clean electricity generation capacity that would otherwise be curtailed.

Most elected politicians are guided by near term public opinion, not physics and engineering. Often politicians incent grid connected clean interruptible electricity generation. However, interruptible electricity provides little direct benefit to clean electricity systems that need dependable, not interruptible, power. However, interruptible electricity can potentially be used to drive INGs, the output of which can feed FNRs.

Another major cost efficiency improvement lies in safe accessible interim storage of fission products. These isotopes have half-lives of less than 30 years. It makes no sense to spend tens of billions of dollars on this interim storage when a few hundred million dollars is more than sufficient. Fission product isotopes naturally decay away in less than 300 years.

Regrettably, most elected governments have either ignored the opportunity for deployment of sustainable nuclear power, or worse, for irrational reasons they have legislatively opposed it.

As a result, present Canadian and US governmental plans for halting climate change are ineffective.

In Ontario, where battery electric automobiles are being successfully promoted, for the next decade, due to repeated governmental delays relating to refurbishment and upgrading of nuclear power capacity, most of the electricity for powering these vehicles will still be generated by combustion of natural gas,

Governmental policy flip-flops with respect to nuclear power deployment have a tremendous cost, especially with respect to work force training.

Today there is little governmental appreciation that:
a) The existing and presently planned thermal neutron power reactors will deplete the known

economic natural uranium resource before 2070;
b) During normal operation **heavy-water cooled power reactors (CANDU reactors) are 2X more energy efficient and 4X more TRU production efficient than Light Water Reactors (LWRs);**
c) As the rare uranium isotope U-235 resource is depleted the aforementioned LWR inefficiencies will have a major impact on the future cost of dependable power;
d) The term **sustainable nuclear power** refers to nuclear power that, due to use of the abundant fuel U-238 instead of the rare fuel U-235, is **potentially available for millennia**.
e) Suitably designed liquid sodium cooled FNRs use TRU to produce **sustainable nuclear power**;
f) The maximum **sustainable nuclear power** that can be supplied by a FNR **is limited by the size of its TRU inventory;**
g) From the perspective of young people it is crucial to maximize the total TRU inventory by:

1. Making all new nuclear power reactor types either CANDU, ING or fuel sustainable FNR. The USA's past choice of LWRs in place of CANDUs was in effect a choice to reject the extra TRU and extra energy efficiency provided by CANDU reactors in order to minimize initial capital cost. That choice has greatly reduced the present and future TRU availability. If the existing LWRs were instead CANDUs there would be 4X as much TRU readily available in used power reactor fuel in the USA.
2. Efficient recovery of TRU from used nuclear fuel;
3. Preventing expensive long-term burial of TRU. The entire NWMO concept of deep geological storage of unprocessed used CANDU fuel is wrong;
4. Stopping intentional consumption of TRU in thermal neutron (water cooled) reactors. TRU must only be used in circumstances where it replaces itself;
5. Recycling of used LWR fuel in CANDU reactors to maximize both energy generation and TRU recovery;
6. Supplementary production of TRU via ING equipment;
7. Early deployment of fuel sustainable FNRs and INGs to achieve maximum practical TRU inventory growth;
8. Supplementary TRU production, using the high energy neutrons produced by fusion of light element isotopes.

The main concern going forward is maximizing production of TRU, which in many countries, including Canada, requires a complete reversal of existing federal government policies.

Even under the most favorable circumstances fully meeting the future dependable power requirement with fuel sustainable INGs and FNRs will also require a combination of:
a) Finding new concentrated natural uranium ore bodies;
b) A major world human population reduction.

8. Uranium Recovery From Sea Water:

a) An additional benefit of FNRs is the potential to continuously operate a FNR from U recovered from heat sink sea water. This U naturally occurs in sea water at a low concentration of **about 3 X 10^-9 g U / g seawater.**
b) At this low U concentration of uranium in sea water it is not possible for a thermal neutron reactor to harvest U-235 as fast as it is consumed. However, in natural uranium U-238 is 140X more abundant than U-235. If the reactor is designed to br fueled with U-238 instead of U-235, then there can be sufficient uranium recovery from sea water to continuously power the reactor.

9. The Natural Uranium Source Constraint Varies with Reactor Technology Chosen:

CANDU reactors usually use natural uranium (0.7% U-235, 99.3% U-238) as fuel.

If CANDU reactors, that **require fuel replacement every 1.5 years**, are used to meet the world thermal load and the CANDU fuel requirement is **100 tonnes of natural uranium per 1000 MWe-years**, there would be a CANDU fuel requirement of:
(100 tonnes natural uranium / 1000 MWe-years) X 15,000 reactors X 300 MWe / reactor
= 45**0,000 tonnes natural uranium / year**

The present total known and projected economic world natural uranium resource, as published by the World Nuclear Association, is estimated to be about:
6,100,000 tonnes.

The reason for this resource limit is not the fraction of U in Earth's crust, it is the fraction that occurs in economic ore concentrations, usually s a result of historic aqueous conditions. Average granite contains 2 ppm to 3 ppm of uranium. Average sedimentary rock contains 3 ppm to 5 ppm of uranium. Sea water contains 0.003 ppm U. However, the U concentration needs to be over 2000 ppm to begin to be economic and known rich ore bodies contain up to 200,000 ppm. Unlike other metals that mostly exhibit a single oxidation state, U has 4 aqueous oxidation states (+3, +4, +5, +6). The parameters that lead to natural ore aqueous concentration vary with the oxidation state. Hence the probability of natural formation of concentrated U ore bodies is relatively low.

The price of natural U has to increase more than 10X to significantly increase the natural uranium supply. That price increase is more than enough to justify the power industry switching from thermal reactors to fast neutron reactors.

If only CANDU reactors are used for total fossil fuel displacement, the present known economic natural uranium resource would be consumed in only:
(6,100,000 tonnes U) / (450,000 tonnes U / year) = **13.55 years**.

If just Light Water Reactors (LWRs) are used in place of CANDUs for total fossil fuel displacement the present known economic natural uranium resource would be consumed twice as fast in:
13.55 years / 2 = 6.78 years.

Hence, due to lack of abundance of concentrated natural uranium ore bodies, thermal neutron (water cooled) nuclear reactors cannot sustainably supply sufficient clean power

to displace fossil fuels. This conclusion does not materially change even if the natural uranium resource is doubled or tripled.

10. Harvesting TRU by Consuming Natural Uranium in CANDU Reactors is Better:

TRU is produced when excess thermal neutrons are absorbed by the abundant uranium isotope U-238. In CANDU reactors the net TRU production rate is about 4 grams TRU / kg of natural uranium used as compared to 1 gram TRU / kg of natural uranium used in LWRs.

Hence the used CANDU fuel could potentially provide about:
6,000,000 tonnes U X (.004 tonne TRU / tonne U)
= 24,000 tonne TRU
as compared to:
24,000 tonne TRU / 4 = 6000 tonne TRU
if LWRs were used instead of CANDUs.

11. Each 0.2 tonne of TRU recovered from used nuclear fuel can be applied to make one tonne of Fast Neutron Reactor (FNR) core fuel.

Hence the recoverable TRU potentially available from existing used CANDU fuel would be sufficient to produce:
24,000 tonne TRU X (1 tonne FNR core fuel / 0.2 tonne TRU)
= 120,000 tonnes FNR core fuel.

12. Each 300 MWe FNR needs about 102 tonnes of core fuel or about

(85 tonnes active core fuel rods plus 17 tonnes cooling core fuel rods)

which allows construction of:
(120,000 tonne FNR core fuel) X (300 MWe / 102 tonnes core fuel)
= 1176 X 300 MWe fuel sustainable FNRs
without reliance on TRU from other sources.

Thus, while present fossil fuel usage indicates a world need for:
15**,000 X 300 MWe FNR power capacity**,
the present known natural uranium resource, if used exclusively for fueling CANDU reactors, will only provide sufficient TRU for construction of:
1176 X 300 MWe of fuel sustainable FNRs.

Hence, Intense Neutron Generators (INGs) are required to make more TRU.

The projected shortage of TRU and hence the corresponding shortages of sustainable and dependable clean power capacity may take decades to correct via supplementary TRU formation. Hence immediate commencement of ING work is of paramount importance.

13. Initial Harvesting TRU From Existing Used CANDU Fuel:

Ontario presently has an inventory of **about 60,000 tonnes of used CANDU fuel containing about 0.4% TRU.** This inventory should be used to make about 1200 tonnes of FNR Core Fuel
(60,000 tonnes Used CANDU Fuel) X (.004 tonne TRU / tonne Used CANDU Fuel) X (1 Tonne FNR core fuel / 0.2 tonne TRU)
= 1200 tonnes FNR core fuel
which is sufficient to immediately make about:
(1200 tonnes FNR core fuel) / 102 tonnes core fuel per 300 MWe FNR)
= 11.76 X 300 MWe fuel sustainable FNRs.

By 2070 Canada's projected human population will be about 60,000,000, so to continue meeting its present average per capita energy use Canada would need about:
[60,000,000 persons X **10 kWt / person** X .75 X 0.3 kWe / kWt X 1 MWe / 1000 kWe]
= **450 X 300 MWe fuel sustainable FNRs.**

If, via aggressive energy conservation, the **average per capita Canadian energy usage is halved,** then in 2070 Canada will still need:
225 X 300 MWe fuel sustainable FNRs

14. Producing TRU Using ING Equipment Is Essential

An alternate route for obtaining TRU is to produce it using Intense Neutron Generator (ING) equipment. The required apparatus consists of a 1 GeV proton accelerator, a flowing lead-bismuth target that produces neutrons by spallation, a Be neutron multiplier, heavy water and a sub critical U-238 / TRU neutron absorption blanket.

Producing TRU by this method should preferentially be done using inexpensive electricity that would otherwise be curtailed.

Each 1 GeV proton incident on the ING target with a Be neutron multiplier causes production of at least 25 thermal neutrons. The TRU production rate is effectively further doubled by use of a sub critical blanket. The resulting TRU should then be concentrated in a re-crystalization cascade in the same manner as TRU is obtained from used CANDU fuel.

15. Summary:

1) The consequences of climate change, especially with respect to human migration are much worse than has been conveyed to the public.

2) Thermal neutron (water cooled) nuclear reactors cannot sustainably prevent further combustion of fossil fuels.

3) FNRs can sustainably fully displace fossil fuels provided that there is a sufficient TRU inventory.

4) TRU can be obtained from used CANDU fuel, by FNR breeding and by use of INGs.

5) Realizing a sufficient TRU inventory by the time that the economic natural uranium resource is exhausted will require careful long term planning and immediate major capital commitments in CANDU reactors, FNRs and INGs.

16. Part 1 Appendix – Governmental Policy Failures:

1) Canada is presently exporting about 90% of its natural uranium production. In terms of future supply of clean energy for the benefit of Canadians, this export of our limited natural uranium resource at a low price is foolishness beyond description. We should instead be exporting energy intensive products.

2) As of June 2023 the Canadian government continues to oppose CANDU fuel reprocessing for TRU recovery. Absent TRU based fuel, financing of FNRs and INGs by third parties is impossible.

3) As long as the federal government continues to legislatively and financially oppose them, fuel sustainable FNRs will not exist in Canada. Then deployment of FNRs will be further delayed as long as the provinces fail to meet the required equipment deployment schedules or keep postponing implementation of new cost based retail electricity rates. These collective delays will result in near-term dependable clean power shortages.

4) Our society relies on availability of low-cost dependable power for basic functions such as production and transportation of food and supply of fresh water. A TRU shortage will cause the cost of clean dependable electricity to become very expensive and will slow deployment of clean dependable power. Continuing use of fossil fuels in place of clean dependable power will cause ever higher dry and wet bulb temperatures.

5) Prior to 2023, the Canadian federal government had a tax policy that discouraged use and deployment of new nuclear power for climate change mitigation. That policy missed the real need.

6) Adoption and promotion of Small Modular Reactors (SMRs), that require enriched uranium fuel, is a total diversion from the main goal of sustainable climate change relief. Reactors that need enriched uranium fuel are several-fold less efficient at both energy and TRU production than are CANDU reactors and also have nuclear waste disposal challenges. Furthermore, at present the principal source of enriched uranium fuel is Russia, which is politically unreliable.

7) As of 2023 the Canadian federal government continues to squander tens of billions of dollars on new fossil fuel infrastructure instead of investing in CANDU reactors, nuclear fuel recycling, FNRs and INGs to supply clean, dependable and sustainable nuclear power.

8) A fossil carbon tax provides no immediate CO_2 emission reduction benefit if consumers of fossil fuels cannot access an economic alternative source of dependable clean power. In this respect the province of Ontario foolishly preferentially exports, at a low price, its excess clean interruptible electricity to the USA instead of allowing Ontario residents to access that low marginal cost clean interruptible electricity for economic displacement of fossil fuels.

9) A necessary immediate federal government policy change is for the Nuclear Waste Management Organization (NWMO) to contract for **permanently accessible dry storage** for used nuclear fuel components, in depleted mines in stable granite rock formations that are high above the local water table, instead of inaccessible used nuclear fuel storage in unstable limestone or salt formations that are far below the local water table. In this respect the geology of south-central British Columbia is more favorable for safe interim storage of used nuclear fuel components than is the geology of Ontario.

10) Another necessary legislative change is to allow electricity distributors unrestricted access to the public internet for the purpose of the signaling required to enable fair and smooth delivery of interruptible electricity to consumers.

11) **In summary, neither the Canadian federal nor provincial government plans relating to clean power directly address the real climate change problems. The most pressing policy problem is the federal one relating to nuclear fuel reprocessing, because it prevents the provinces from acting independently with respect to INGs and FNRs.**

17. Part 1 Appendix – Recognition of Physical Reality

a) The significant available sources of clean energy are wind, solar and hydro-electric generation, thermal neutron reactors and fast neutron reactors. However, wind and solar generation provide interruptible power, not dependable power. Hydro-electric power is seasonal.

b) The full costs of converting interruptible power and seasonal power into dependable power are seldom recognized by the general public. In addition to the basic costs of renewable generation are the costs of backup generation capacity, curtailment of excess production, grid protection, additional transmission to enable delivery of power to where it can be used, energy storage, frequency stabilization and additional grid operation and maintenance.

c) A fossil carbon tax will raise the price of using fossil fuels, but until consumers have an economic, sustainable and dependable alternative clean power source a fossil carbon tax will provide little climatic benefit.

d) During the summers of 2022 and 2023 there were record droughts and wild fires in North America and Europe. There was record extreme weather elsewhere. The projections for 2024 are worse.

e) Gradually people around the world are recognizing that the only economic and sustainable source of clean dependable electricity is nuclear power.   Countries such as China are buying: control of uranium mining companies, uranium forward contracts and spot market uranium in order to to secure enough natural uranium to power their light water reactors for the projected reactor service lives.

f) By COP 28 in November 2023 there was international agreement that to reduce CO2 emissions the existing nuclear power capacity must be at least tripled by 2050, irrespective of the cost of nuclear electricity as compared to the cost of electricity obtained from combustion of natural gas.

g) The knee-jerk political reaction is to build yet more water cooled power reactors.

h) The present total world nuclear power reactor capacity is about 1400 GWt. Even if this capacity is tripled to 4200 GWt by 2050, it will be nowhere near the 15,000 GWt required to prevent continuing emission of CO2 to the atmosphere. The closest realistic date for stopping further CO2 emission is 2070.

i) Most existing water-cooled nuclear power reactors are very fuel inefficient and primarily rely on the rare uranium isotope U -235.

j) A LWR recovers about 0.5% of the energy contained in its natural uranium fuel feed stock and produces about 1 gm TRU per kg of natural uranium feed stock. It requires 200 tonnes of natural uranium to produce about 1 GWe-year of electricity.

k) A CANDU reactor recovers about 1% of the energy contained in its natural uranium feed stock and produces about 4 gm TRU per kg of natural uranium feed stock. It requires about 100 tonnes of natural uranium to produce about 1 GWe-year of electricity.

l) Natural uranium is about 0.7% U-235 and about 99.2% U-238.

m) There is not enough economic natural uranium and hence U-235 to sustainably displace fossil fuels using water cooled reactors.

n) By comparison, a properly designed Fast Neutron Reactor (FNR) supported by appropriate fuel reprocessing recovers 100% of the potential energy contained in its fuel and produces TRU at about 80 gm / kg U;

o) The projected world thermal power increase due to electrification in developing countries is huge. If we wish to slow climate change driven human migration , we must help developing countries afford electric air conditioning fed by nuclear electricity.

18. Part 1 Appendix - Examples of Political Denial of Physical Reality:

a) During 1967, the Canadian federal government insisted on proceeding with a heavy water plant at Glace Bay, Nova Scotia, in spite of being warned in writing that the plant would quickly fail due to corrosion by sea water. $125 million 1967 dollars and about one year later the plant was a total write off due to salt water corrosion.

b) During the 1970s Ontario Hydro continued construction of new coal fired generation even though by 1970 there was ample experimental evidence of CO2 accumulation in the atmosphere and the CO2 green house effect. Those coal fired electricity generation plants were write offs half way through their projected life.

c) Circa 2002 the government of Ontario applied electricity system capital costs (global adjustment) to kWh instead of peak kW. The effect is to prevent use of low marginal cost kWh for displacement of fossil fuels. To this day successive provincial governments have been politically afraid to fix this problem.

d) The Harper Conservative government defunded AECL such that today there is no Canadian government organization that can take the lead on FNRs and nuclear fuel reprocessing. Similarly the Harper government funded the NWMO to bury rather than preserve TRU. Successive Trudeau governments have failed to address these issues.

e) Circa 2007, the Province of Ontario over-committed to wind and solar electricity generation without considering the costs of integration of these intermittent energy sources into the Ontario electricity grid. Ontario electricity rates still have not been changed to make effective use of wind and solar electricity generation for fossil fuel displacement.

f) In 2012 major Canadian nuclear waste disposal decisions by the NWMO potentially costing tens of billions of dollars were still being made without considering the climate change consequences or FNR use of used CANDU fuel and neutron activated zirconium.

g) During the period 2016 to 2024 the Canadian government invested $30 billion in the Trans Mountain pipeline without considering its climate change consequences.

h) During the period 1990 to 2022 most new nuclear power construction in the USA was halted and fully functional nuclear reactors were closed due to price competition from natural gas without consideration of the climate change consequences;

19. Limited Life of Economic Natural Uranium Resource:

a) The World Nuclear Association indicates that the economic natural uranium resource is about 6 million tonnes;

b) CANDU reactors consume natural uranium fuel at a rate of about 100 tonnes / GWe-year;

c) Light water reactors (LWRs) are about one half as natural uranium efficient as are CANDU reactors.
d) The total world operating reactor capacity is about 400 Gwe;
e) The world power reactor capacity is dominated by LWRs
f) Thus the world consumption of natural uranium is:
400 Gwe X 2 X 100 tonnes / Gwe-year = 80,000 tonnes / year
g) There is sufficient known natural uranium to power existing reactors for:
6,000,000 tonnes / (80,000 tonnes / year) = 75 years;

h) At COP28 22 industrialized nations adopted a policy resolution to triple existing world nuclear reactor capacity by 2050.

i) However,with 3X that many operating thermal neutron reactors the presently known natural uranium supply will be depleted in only

75 years / 3 = 25 **years.**

j) This time is less than the time reasonably required for FNR development and deployment.

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Fast Neutron Reactors (FNRs) for Mitigation of Climate Change (Part 2, Hardware Issues)

C. St. L. Rhodes
Xylene Power Ltd., Sharon, Ontario, Canada
CSLRhodes@gmail.com. Charles.Rhodes@xylenepower.com

Abstract:
As shown in Part 1, Fast Neutron Reactor (FNR) technology must be adopted to provide economic, sustainable and dependable clean power for mitigation of climate change. The only economic, reasonably safe and suitable FNR coolant is sodium. Urban FNR siting is required to enable economic district heating. The use of a sodium pool at an urban site triggers multiple safety issues relating to elevation, enclosure design and fire prevention/suppression. The core fuel is sodium bonded metallic (TRU, U, Zr) with prompt critical reactivity suppression. The fuel tube / fuel bundle material is HT9. The normal coolant temperature is ~ 470 degrees C controlled by thermal expansion, Temperature set point changes are by changing fuel bundle geometry. The primary/secondary heat transport is by natural circulation and induction pumping. External heat transport by low pressure KNO3/NaNO3 and air. External district heating by condenser cooling water feeding remote heat pumps and remote cooling towers. Reactor fuel bundles are transported in suitable shielded shipping containers to/from a rural remote fuel reprocessing site.

Nominal reactor size is 300 MWe/1000 MWt. FNR site must allow emergency dissipation of 80 MWe of fission product decay heat via steam release. FNR enclosure must withstand worst case natural events and must safely manage credible man-made attacks. Enclosure must provide for argon cover gas expansion/contraction, must have suitable airlocks, must have suitable internal material handling equipment, must provide safety in depth and must provide for economic long term maintenance while operating at reduced power. Irrational governmental and public opposition to this technology must be defeated. There is no practical alternative.

1. Essential FNR Design, Construction and Operation Features:

- A practical FNR consists of concentric core, blanket, cooling and heat exchange assemblies immersed in a sodium pool;
- Pool elevation must be sufficient to prevent flooding by water over the lifetime of the FNR;
- External enclosure must be sufficiently robust to withstand tornadoes, hurricanes, air borne debris, earthquakes and low angle aircraft impacts;
- Enclosure must be equipped for sodium fire suppression and emergency roof repair sufficient to counter man portable antitank guided missiles;
- Airlocks for fuel bundles, heat exchange bundles and humans;
- Urban or industrial zone siting for district heating energy efficiency;
- Modular fuel bundles and intermediate heat exchange bundles;
- Prompt neutron criticality suppression;
- Polar gantry crane;

- Argon cover gas;
- Interior argon bladder storage;
- Chemically compatible heat transfer fluids;
- Flex radial pipe sections to accommodate thermal expansion;
- Isolated interior service space heat rejection;
- Passive temperature control;
- Airlocks for fuel bundles, heat exchange bundles and humans;
- Multiple independent heat transport systems each with fluid drain down;
- Modular turbo-electric power plant with at least 15% spare capacity;
- No off site exclusion zone;
- Grid independent backup power for emergency rejection of fission product decay heat and sodium pool enthalpy;
- 20% of fuel bundles to be swapped out at 6 year intervals;
- Shared remote fuel reprocessing facility;
- Transportable hot fuel bundles;
- A fuel bundle must not go critical if its transportation container is immersed in water;
- Governmental investment and regulatory cooperation is necessary to achieve fuel bundle assembly automation and safety compliance without serious delays or excessive costs.

A previous paper identified that large scale deployment of CANDU Reactors, Fast Neutron Reactors (FNRs) and Intense Neutron Generators (INGs) is required to fully displace present fossil CO2 emissions. This paper identifies the essential FNR hardware requirements and features. The ING hardware requirements are outlined in ING Status Report July 1967 AECL-2750.

Stopping further fossil CO2 emission to the atmosphere will require
the equivalent of a new fleet of about 15,000 X 300 MWe of fuel sustainable FNRs. At least 225 of these FNRs will have to be located in Canada.

FNRs convert abundant fertile atoms into fissile atoms and then fission the fissile atoms. FNRs are power capacity limited by their TRU inventory. TRU is a mixture of heavy atoms with atomic numbers greater than 92 that can be extracted from used CANDU fuel, or bred with FNRs, or made using Intense Neutron Generators (INGs).

Urban and industrial zone siting of FNRs is of great importance in terms of minimizing the total required FNR capacity.

In 1965 Canada had the technical capacity to make INGs. From 1965 to 1990 Canada made large CANDU reactors and supporting heavy water separation systems. From 1964 to 1994 the USA demonstrated the capacity to make and operate sodium cooled Fast Neutron Reactors.

Various incompetent and corrupt politicians destroyed the organizations that harbored these skill sets. Today, if young people want to survive, they are going to have to learn these skills, which today reside mainly with retired persons who are more than 75 years of age.

Detailed engineering, prototype development and deployment planning for FNRs cannot be financed by either provinces or private industry until the federal government enables efficient sourcing and reprocessing of FNR fuel.

Supply of sufficient economic clean (non-fossil) dependable power for sustained fossil fuel displacement requires large scale deployment of Fast Neutron Reactors (FNRs) fueled by the abundant uranium isotope U-238 with supporting TRU formation, TRU concentration and nuclear fuel reprocessing.

TRU (TRans uranium actinides) are atoms with atomic numbers greater than 92. TRU forms when U-238 is exposed to a thermal neutron flux. In a thermal neutron reactor TRU is often considered to be a long-lived nuclear fuel waste. In a FNR TRU enables fuel sustainable operation. Of particular importance are Intense Neutron Generators (INGs) with sub-critical neutron multipliers to increase the initial TRU inventory.

It is critical for present young people to grasp that if they fail to promptly deploy sufficient FNR and ING capacity they and their descendants will all become victims of CO2 induced climate change. The largest near term risk is uncontrolled human migration away from the tropics driven by the rising wet bulb temperature.

In this respect young people should ignore the false and deceptive claims made by governments, utilities and fossil fuel companies and should study the relevant physics for themselves.

For humans to survive and prosper, the world needs to deploy about 15,000 X 1 GWt of FNR capacity to arrest climate change. **That is about one new 300 MWe FNR per day every day for the next 45 years.** If that seems like a daunting challenge remember that during WWII, without the aid of computers or electronic desk calculators, my parents generation built the equivalent of three four engine bombers every hour and 3 ocean going ships every day. It is a doable objective if you focus on it. The alternative is to accept extinction by climate change.

Unless each of you convey to the public and the government the urgency of the present situation, you and your descendants are all doomed.

Today, technical expertise in energy matters is not sufficiently respected by the persons who populate our government and civil service. We urgently need political leadership with the combined skills of the late Sir Winston Churchill and FDR and we need technical leadership with the combined skills of Leslie Groves, Robert Oppenheimer, Hyman Rickover and Canada's WWII Minister of war production **C.D. Howe.**

It is not necessary to get hung up with elaborate computer models. The Pickering CANDU reactors were designed using slide rules.

2. FNR Coolants:

FNR coolants must meet a number of physical parameters including low melting point, low vapor pressure at their working temperature, high atomic weight, low neutron absorption cross section, structural metal compatibility and acceptable cost.

The FNR primary coolant choices that have been experimentally tested are sodium (Na), lead-bismuth (Pb-Bi) eutectic, and various molten salt mixtures. When Na-23 captures a neutron it becomes Na-24 which decays to stable Mg-24 with a 15 hour half life. When Bi-209 captures a neutron it becomes Bi-210 which decays to Po-210 with a 5 day half life. However, Po-210 is an alpha emitter with a 138 day half life and is one of the most toxic materials known to mankind. From a worker health and safety perspective a power reactor containing large amounts of Po-210 is impractical to maintain.

The problem with salt mixtures is that their melting points are too high. Salt mixtures require fuel tubes made of mono isotopic Mo to meet the combined corrosion resistance, swelling resistance, melting point and neutronic requirements. The salt mixtures generally also require yet another isotope separation to separate Cl-35 and Cl-37. The combined costs of Mo fuel tube fabrication and Mo and Cl isotope separations are prohibitive.

Hence, practical power FNRs have almost all used primary sodium cooling. This paper assumes that Na primary cooling is the only technology suitable for large scale FNR deployment.

However, Na burns in air and reacts explosively with water. Hence Na fire prevention and suppression sets many aspects of practical FNR Nuclear Power Plant (NPP) design.

3. Major FNR Advantages:

A Fast Neutron Reactor (FNR) produces heat by fast neutron fission of TRU while simultaneously forming new TRU. Fast neutrons have kinetic energies of about 2 MeV. The use of fast neutrons in the reactor core gives a FNR major advantages in terms of atmospheric pressure coolant, walk away safety, efficient natural uranium utilization and disposal of long lived high atomic weight nuclear waste.

4. Elevation, Tornadoes, Hurricanes, Earthquakes:

A sodium cooled power reactor pool will likely contain over thousand tonnes of liquid sodium. It is essential that this sodium never contact water. If flood water flows into the sodium pool large amounts of hydrogen will be produced which will likely spontaneously ignite. The resulting hydrogen fire will likely cause so much equipment damage that other safety systems are rendered inoperative. Hence, sodium cooled FNRs must be sited at sufficiently high elevations that they can never be flooded by water.

A FNR nightmare is a tornado or earthquake that destroys the roof of a FNR enclosure followed by a major rainstorm. Hence a FNR must have a tornado and earthquake tolerant enclosure. Tornadoes routinely drop the local air pressure by about 1.5 psi. Hence the FNR enclosure must withstand a net internal pressure of about 3 psi. On a 30 m diameter enclosure, that is a force of about about 1000 tonnes. To put that force in perspective, most major highway bridges are designed to accommodate multiple 80 tonne vehicles. Hence, from a structural strength perspective, for safety compliance a FNR enclosure should be comparable to a water tight major highway overpass.

Forget about artists conceptions to the contrary.

An issue of great economic importance in terms of energy conservation is urban and industrial zone siting of FNRs so that the low-grade heat rejected by thermal electricity generation can be used for district heating and so that competent service and emergency response personnel can be located nearby. Hence, FNRs must be designed for safe siting in the middle of major cities. Locating FNRs in cities means that for public safety they must operate at a low pressure and must be passively safe.

In order to economically build and service FNRs in cities the FNR component modules must be truck transportable and airlocks must provide for safe installation and safe removal of fuel bundles and intermediate heat exchange bundles.

4. FNR Description

The FNR described herein incorporates lessons learned during development and testing of the US EBR II, the French Phoenix and Super Phoenix and the Russian BN series reactors. Readers interested in the rational for each FNR design decision should refer to published documents relating to these reactors. In choosing between various design alternatives the author relies on his own 25 years of supervising field installation and maintenance of major electrical, mechanical and combustion equipment.

A basic fuel sustainable FNR consists of the following components shown in Figure 1:
a) An insulated triple wall sodium pool which confines the liquid sodium and is designed to last for centuries (black and dark gray);
b) A central core region where fast fission takes place (red);
c) A blanket region surrounding the core where depleted U-238 atoms slow and then absorb neutrons which escape from the central core (pink);
d)A cooling region surrounding the blanket region where there is minimal neutron flux. Used core fuel bundles are stored in the cooling region for several years before being removed from the sodium pool (pink);
e) A plenum region above the core and blanket where inert gas fission products are stored (orange);
f)A neutron absorption region surrounding the cooling region where liquid sodium absorption reduces the neutron flux to zero (light blue, yellow);
g) An intermediate heat exchange bundle region, above the neutron absorption region, where heat is extracted from the sodium pool using internal pumped NaK (light green);
h) Gasketed NaK pipe flanges to enable heat exchange bundle replacement;
i) Radial NaK pipes with flex sections to accommodate differential thermal expansion (gold and blue);
j) An overhead space filled with argon gas that allows polar gantry crane manipulation of both fuel bundles and intermediate heat exchange bundles;
k) An overhead polar gantry crane (white);
l) Indicator tubes to convey local reactor conditions to overhead instrumentation.

The FNR core, blanket and cooling regions contain fuel bundles fabricated from HT9 chrome-steel that are subject to fast neutron damage and are intended to be periodically replaced.

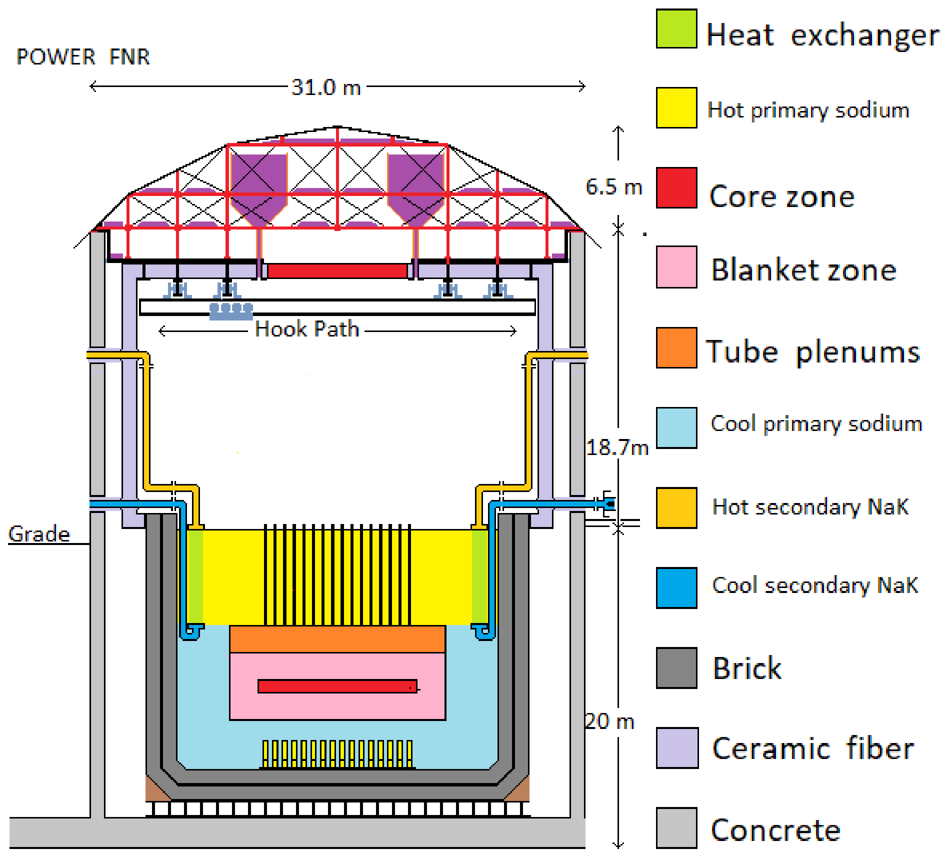

Figure 1

6. FNR Safety Feature Summary:

Robust high elevation central nuclear island;
Perimeter turbo-generator halls;
Site corner cooling towers;
No water or high pressure in the nuclear island;
Passive high temperature shutdown;
Two independent cold shutdown safety mechanisms;
Ability to load follow from 10% to 100% of reactor full load rating;
Prompt neutron criticality disassembly;
Gravity safety default;
Interior argon bladders
Redundant radial heat transport
Sodium fire suppression

7. FNR Fuel:

The FNR core fuel is a metallic alloy initially consisting of 20% TRU, 70% U and 10% Zr. The role of the Zr is to prevent Pu in the TRU combining with the adjacent Fe-Cr fuel tube material to form a low melting point Pu-Fe eutectic. Metallic fuel is preferred because it is easy to reprocess and it allows use of sodium within the fuel tubes to provide both good thermal contact between the fuel rods and fuel tube and to absorb corrosive fission products. This sodium internal to the fuel tubes also plays an important role in suppressing undesired prompt neutron criticality and in mechanical fuel rod sorting.

8. FNR Pool Coolant:

The chosen FNR pool coolant is pure sodium. Its manageable toxicity, abundance, low melting point, steel compatibility, and good neutronic advantages outweigh its fire risk.

9. Maximum Coolant Sodium Operating Temperature:

Use metallic fuel rods for ease of fuel reprocessing.
The fuel fabrication involves vacuum suction of core fuel alloy into a quartz tube.

During normal FNR operation the temperature on the fuel rod center line is higher than at the outside of the fuel rod. There is also a temperature gradient along the length of the fuel rod. The hottest point is at the top center of each core fuel rod.

The melting point of Pu is about 650 deg C. However, Pu under goes a phase change at 602 deg C. Thus for fuel dimensional stability the hottest point in the fuel assembly should be kept under 602 deg C.

Allowing for a normal 60 deg C radial temperature differential and a 50 deg C safety margin to account for slightly bent fuel tubes gives a normal maximum sodium temperature of about 490 deg C. To achieve long term gasket durability this temperature maximum is reduced to 470 degrees C. Russian operation at 525 degrees C with thinner fuel rods seems to indicate use of superior gasket materials.

10. Fuel Heat Exchange

Within the sodium pool, heat transport from the fuel rods to the sodium is by thermal conduction.
The temperature of the liquid sodium coolant, which is in good thermal contact with the fuel tubes will rise to approach the fissile fuel set-point temperature.
Sodium heat transport from the fuel tubes to the heat exchange bundles is by sodium natural convection.

11. Heat Transport Into and Out of the Sodium Pool:

FNR heat **flows into or out of the sodium pool via isolated induction-pumped NaK that flows inside the intermediate heat exchange bundles. NaK is** liquid down to room temperature, is practical from a service perspective, can be induction pumped, can be reliably drained to a dump tank and then reinserted, and in the event of a heat exchange tube leak does not explosively react is with sodium or nitrate salt.

The NaK is at a higher pressure than the sodium, so in the event of a intermediate heat exchange bundle leak NaK flows into the sodium pool rather than radioactive sodium entering the non-radioactive NaK loop. Thus, the sodium pool may need ongoing filtering to remove K after such a leaks.

The NaK is further isolated by atmospheric pressure nitrate salt, synthetic heat transport fluid or Pb-Bi loops that convey heat to or from the nuclear island.

Due to significant linear thermal expansion, all the radial NaK pipes must have flex sections. The intermediate heat exchange bundles are supported by the sodium pool inner wall. The other end of the radial piping is supported by the concrete enclosure structure. Due to thermal expansion these support points can easily shift as much as 20 cm with respect to each other.

Every NaK heat transport loop has a dedicated below grade dump tank that is used to for thermal isolation, service and potential fire suppression. There are many redundant NaK loops to ensure that there is always sufficient heat transport capacity for removing both fission product decay heat and sodium pool enthalpy.

Heat transport is mainly by NaK within the nuclear island and by other fluids off the island. Multiple independent heat transport loops and backup power systems are required to ensure that power is always available for rejection of fission product decay heat, irrespective of electricity grid status.

12. Other FNR Material Choices:

Nitrate salt features high heat capacity, low fire risk, high and medium temperature operation;

Pg-Bi provides a wider temperature range than nitrate salt, but at a higher price;

Synthetic Heat Transport Fluid: features high heat capacity, minimum fire risk, medium and low temperature operation;

Turbine working fluid; high pressure water/steam, conventional 400 deg C steam turbo-generator system;

The FNR maximum sodium coolant operating temperature of 450 C to 500 C is compatible with: metallic fuel, NaK coolant, HT9 fuel tubes, gaskets, induction pumps, nickel alloys and stainless steel, and nitrate salt;

The FNR fuel assembly is composed of core and blanket fuel bundles. Each core fuel bundle is an assembly of vertical parallel fuel tubes, each about 3 / 8 inch OD. Each vertical fuel tube contains a 0.25 inch diameter core fuel rod sandwiched between upper and lower stacks of blanket fuel rods.

The intermediate heat exchange bundles are fabricated from high temperature rated nickel steel alloys. These bundles are not subject to a neutron flux and hence are not subject to nickel related swelling or embrittlement and, apart from a thin surface coating of sodium, will not become radioactive. Once the Na-24 decays and the heat exchange bundle outside surfaces are cleaned with water to remove adhering

Na and NaOH the heat exchange bundles can be safely manually repaired.

Note that the totality of performance objectives requires a sodium pool inside diameter of about 20 m to realize a FNR power level at about 1000 GWt or 300 MWe.

13. FNR Fuel Cycle:

A fuel sustainable FNR fuel assembly has a central core zone entirely surrounded by a fertile blanket zone, In the core zone fast neutrons fission TRU atoms. Excess neutrons emitted by these fast fission reactions diffuse into the blanket zone where these neutrons gradually lose energy and are absorbed by U-238 atoms to become U-239. The U-239 decays with a half life of 24 minutes into Np-239 which then decays with a half life of 2.3 days into Pu-239. Note that about half of these new TRU atoms are in the blanket zone, not the core zone. Due to the spectrum of neutron energies in the blanket part of the Pu-239 becomes Pu-240 and other TRU atoms. Spontaneous fission of the Pu-240 prevents use of TRU for nuclear weapon proliferation.

At six year intervals about 20% of the FNR fuel is reprocessed. The reprocessing mechanically sorts blanket fuel rods, rejects fission products from the core zone, moves new TRU atoms from the blanket zone into the core zone and refills the blanket zone with new U-238 atoms.

This periodic fuel reprocessing can continue as long as there is a supply of U-238 fuel. Since U-238 is an Earth abundant isotope, and can also potentially be harvested from the ocean, with ocean front reactors and suitable fuel reprocessing this process is fuel sustainable.

Once operating a properly designed FNR produces more TRU than it consumes. That excess TRU can be used for starting other FNRs,

14. Passive Temperature Control:

FNRs generally rely on thermal expansion of the fuel assembly for moment by moment control of the reactivity and hence the average fuel temperature. The FNR reactivity must decrease as the average fuel temperature increases. In this respect the main TRU component plutonium is useful due to its large thermal coefficient of linear expansion (TCE = 50 X 10^-6 / deg C).

Minor changes in reactivity are achieved via thermal expansion/contraction of the fuel assembly. As the fuel temperature rises the fuel assembly reactivity decreases stopping the fission reaction and vice versa.

At the reactor set point temperature the reactivity is zero so the FNR maintains a constant thermal power.

The FNR set-point temperature is controlled by mechanical adjustment of the core fuel geometry. The core region consists of both movable and fixed fuel bundles. To make a major change in the reactor set point temperature movable core fuel bundles are vertically displaced with respect to adjacent fixed core fuel bundles.

As the movable fuel bundles gradually penetrate the matrix of fixed fuel bundles the assembly reactivity increases. At the point of criticality, where the reactivity swings positive, the fission heat output increases and the fuel temperature rises. The fission heat causes thermal expansion of the fuel, the fuel assembly and the adjacent sodium coolant atoms. That thermal expansion lowers the net reactivity which stops the rise in fuel temperature.

The FNR average fuel set point temperature is normally nearly constant. In designing and operating a FNR care must be taken to ensure that the cool ends of the core fuel rods do not become too cold with respect to the reactor set point temperature. That circumstance can potentially lead to the center line temperature of the hot ends of the core fuel rods rising so high that there is local fuel center line melting.

FNR temperature set-point adjustment and cold shutdowns require larger changes in reactivity and are achieved by mechanically adjusting the fuel bundle geometry. There are two independent shutdown systems to provide certainty of shutdown action.

15. Gravity Safety Default:
The fuel assembly is designed such that the effect of gravity induced changes in fuel geometry is to reduce the fuel assembly reactivity.

16. Prompt Critical Protection:
In the event of a sudden fuel overheat condition thermal expansion/vaporization of the fuel tube contents drives fixed fuel bundle core fuel rods toward the plenum which stops the fusion reaction by reducing the fuel assembly reactivity.

17. Enclosure:
Ensuring that the sodium pool of a 300 MWe FNR will never be exposed to either air or water implies the existence of a robust 31 m diameter cylindrical reinforced concrete enclosure over the sodium pool to ensure continuing air and water exclusion in the presence of a tornado or hurricane.

18. Footprint:
A typical 300 MWe FNR power plant requires a dedicated plot of elevated land (at least 160 m X 160 m) with at least 80 MWt of certain cooling tower heat sinking capacity.

19. Nuclear Island:
The nuclear island is a robust isolated building that must comply with all relevant nuclear safety codes. It contains no piped water and is engineered to prevent water entry or Na leakage and to suppress Na and NaK fires. Its sides are dsigned to withstand a low angle aircraft impact. Its fire suppression system can deal with man portable anti-tank missiles. It contains very few mechanical moving parts. The inner portion of the nuclear island contains the FNR sodium pool covered by an argon atmosphere.

In normal FNR operation, unless an equipment failure is detected, there is no necessity for service or operating personnel to enter the nuclear island. The FNR set point temperature is passively controlled.

The nuclear island connects to the balance of the plant via buried insulated nitrate salt and heat transfer fluid pipes.

Impact sensing and fire sensing are used to determine if an emergency reactor cold shutdown is needed,

20. Heat Transport and Electricity Generation Systems:

Normal heat transport is by NaK within nuclear island and is by nitrate salt or Pb-Bi off the island. Warm up and cool down both require temporary heat transport via synthetic heat transport fluid. Multiple independent heat transport systems are used to ensure that power is always available for rejecting fission product decay heat, irrespective of electricity grid status.

21. Worst Case Accidents:

The key issue in worst case accidents is not equipment protection. It is limiting the maximum possible public liability.

The worst credible FNR accident involves an operating FNR with a roof that is damaged by a tornado or a vertical aircraft impact immediately followed by a rain storm that causes a large hydrogen fire, followed by a hot sodium fire, followed by fuel tube melting and airborne fission products.

The first line of defense against the worst credible FNR accident is a wind, tornado (air pressure) and earthquake tolerant reinforced concrete enclosure. This enclosure should have a roof and walls rated to withstand a net internal pressure of about 3 psi. and redundant 1 m thick side and sheer walls forming a 50 m X 50 m square that can withstand a low angle aircraft impact.

Even a very robust enclosure can potentially be penetrated by a large meteorite or a descending armour penetrating bomb or missile. In that event it is necessary to have certainty regarding stopping the fission reaction, safe rejection of sodium pool enthalpy, safe rejection of ongoing fission product decay heat, and extinguishing of the now lower temperature sodium fire.

The second line of defense is the redundant heat removal and a sodium fire extinguishing system,

The sodium fire extinguishing system consists of several layers of floating steel balls covered by NaCl.

22. FNR Deployment:

Large scale deployment of these fuel sustainable FNRs and the required supporting fuel recycling capacity will likely take at least five decades. Instead of encouraging and supporting this planning work the present Canadian federal government legislatively opposes it. As a result the CO_2 emission reduction targets announced by the Canadian federal government at this time are not sustainable.

23. Argon Bladders:

The sodium pool is covered by argon. During FNR warm up that argon expands. To allow for that expansion without causing major containment forces that argon is vented into atmospheric pressure storage bladders. Then on reactor cool down that stored argon is transferred back into the pool space.

24. Interior Service Space Heat Rejection:

The sodium pool space operates at about 500 degrees C. The sodium pool space is surrounded by an insulated gas tight wall which in turn is surrounded by a 1 m wide service access apace. The service access space is surrounded by yet another gas tight wall. In the event that one or more fuel tubes leak into the sodium radioactive inert gases can accumulate in the argon cover gas. If the inner wall also leaks some radioactivity can migrate into the service space. Should that happen we do not want these radioactive inert gases to leak outside until they have been contained for a sufficient period. Hence the service space is sealed from the outside.

Heat which leaks through the inner wall must be rejected to the outside via a sealed cooling system.

25. Summary:

If mankind is to survive as a species FNR technology must be adopted to provide sufficient sustainable and dependable clean power to displace fossil fuels.

At this time the only practical FNR primary coolant choice is sodium.

Sodium has associated with it significant fire risks which must be faced, especially for urban sited FNRs. For safety compliance a sodium cooled FNR requires sufficient elevation and very robust nested enclosures with interior sodium fire suppression capability.

Distributed FNR's require ongoing fuel bundle reprocessing at a central location.

The design of each fuel bundle transportation container must ensure that the contents will not go critical if the transportation container is immersed in water.

26. Part 2 Appendix-Legislation

Changing the Canadian federal legislation, particularly relating to nuclear fuel reprocessing, is paramount. At this time, other than FNRs, there is no other dependable and sustainable source of clean energy that can sustainably displace mankind's present CO2 emissions. This policy change work must be expedited.

Provincial financing of dependable and sustainable nuclear power generation requires recognition of its economic value to the consumer as compared to interruptible power (renewable electricity) generation. To reflect this value dependable and sustainable electricity should be priced based on the consumer's peak demand measured at times when interruptible power is not available to that consumer. Then electrical and low-grade thermal energy can be priced at the low flat rates required for economic fossil fuel displacement. The necessary metering requires bi-directional communication between the electricity utility and electricity consumers.

Delays in promptly addressing the shortage of economical natural uranium, deployment of CANDU reactors, production of TRU based FNR core fuel and restructuring of retail electricity rates will result in near term dependable clean power shortages.

27. Part 2 Appendix- Funding

Sufficient FNR deployment to displace fossil fuels will require a sustained commitment of public sector resources for which there is a large competing short-term demand.

Failure of national governments to fund development of FNR related fuel reprocessing facilities for supply of clean dependable power will have dire human consequences. As a minimum, dependable electricity will become extremely expensive as will everything in the economy that relies on dependable electricity.

28. Part 2 Appendix – FNR Fuel Supply

Construction of FNRs, even by provinces, cannot be financed without a secure Canadian source of FNR fuel. FNR core fuel is typically about 20% TRU. Since the inception of water cooled nuclear power TRU has frequently been regarded as a hazardous waste material that should be production avoided, fissioned or buried. For the last three decades the federal governments of Canada and the USA have blocked work essential for fabrication of FNR core fuel. For the last six decades the USA has minimized TRU production.

Today we find that far from being a hazard, a large TRU inventory is essential for continuation of the human species on planet Earth. The present low TRU inventory is the result of the complete failure of governments to make long term plans for fossil fuel displacement after it was shown that combustion of fossil fuels causes an ongoing rise in the atmospheric and ocean CO2 concentrations.

From the perspective of a state or provincial electricity utility FNR fuel supply is a federal government responsibility. The electricity utilities are in the business of supplying power and energy to customers, not processing of used reactor fuel, which should be under federal control for protection against terrorism.

In Canada and the USA by far the biggest problem with FNR implementation is ongoing refusal by the respective federal governments to discharge their key roles as regulators and suppliers of FNR fuel. The provincial / state electricity utilities need a reliable source of FNR fuel to enable private sector financing of FNR construction. Yet as recently as June 2023 the Canadian federal government still refused to fund even preliminary work related to FNR fuel supply. In the USA work on FNR fuel supply at INL has been similarly politically paralyzed.

This fuel reprocessing work is not technically complicated. The processes are well known. In Canada we already possess in used CANDU fuel sufficient TRU for at least a dozen 1 GWt FNRs. This asset makes it possible to start inexpensively and expand the facilities as the number of FNRs and INGs grow.

29. Part 2 Appendix – FNR Technical Understanding

From an intellectual perspective the application of FNRs to mitigation of climate change is governed by a combination of astrophysics, fast neutron physics and fast neutron reactor engineering. Today these subjects have almost disappeared from modern Canadian university physics and engineering curricula. There are only a handful of people left alive today who grasp that during the early-1960s Canada was a world leader in fast neutron physics and that from the mid 1960s to mid 1990s the USA was the world leader in FNRs. Those technical leads were squandered by multiple incompetent and corrupt politicians. Most persons in Canada who have deep FNR expertise are well past retirement age.

Today it is up to the younger members of CNS to change the course of Canadian nuclear technology. Otherwise, the increasing wet-bulb temperatures will soon cause massive human migration and then extinction of large animal life on planet Earth.

30. Part 2 Appendix - Essential Changes:

To halt CO2 emissions it will be necessary to make radical governmental policy changes.

a) All federal government cabinet ministers and senior civil servants who approved the Trans-Mountain pipeline (TMP) expenditures must be terminated. From the perspective of climate change mitigation the entire TMP project is a fraud.

b) Fossil fuels, except as necessary to temporarily meet interim Canadian needs, must remain in the ground.

c) Fossil fuel exports must stop. If a nation such as Germany irrationally resists implementation of nuclear power that nation should be left to progressively freeze in the dark.

d) The entire executive of the NWMO must be terminated for cause;

e) The entire "expert" nuclear staff of the Ministry of National Resources must be terminated for cause;

f) The CNSC must simplify its FNR approval process. FNRs built in accordance with a standard approved design must, on completion of normal safety system tests, receive routine approval. The whole approval process must be no more complex than the approval process for a passenger aircraft or a major building.

g) The federal government must immediately fully fund development of an initial FNR fuel production and recycling facility. Without this facility FNRs cannot be financed or deployed by others. This facility will need a neutron spallation TRU production branch.

h) In the interim all new reactors should be of the CANDU type to maximize TRU production. These new CANDU reactors must be configured to load hot fuel to allow consumption of used LRT fuel.

i)With respect to funding we don't need governmental future funding announcements. We need cash in the bank now to pay engineering salaries to get this project moving. To realize that cash immediately stop all federal payments to fossil fuel organizations, stop all payments to the NWMO, and stop all payments to **incompetent and corrupt** personnel that support fossil fuel favoring infra structure policies. Stop all payments for further development of thermal neutron reactors except heavy water cooled CANDUs.

There is no excuse for senior management of the relevant government agencies to not have a good understanding of nuclear physics, nuclear power systems, nuclear waste disposal, electricity systems and the physics of climate change. Further in-depth learning help for increasing their technical understanding in these areas must be provided for newcomers to FNR-ING-Climate Change issues.

New deputy ministers must clean house in the various government agencies, particularly the NWMO, the Ministry of Natural Resources, CNSC, CNL and AECL. FNR deployment decisions must be made based on physics and power engineering, not on irrational emotion, religious bias or uninformed popular opinion. The public must be educated in this area, and their concerns adequately addressed with real facts. Unproductive resource consuming climate change mitigation measures must be halted.

Imagined fears of terrorists obtaining fissile material must be balanced by the **reality** of limiting real and increasing damage due to climate change.

Imagined fears of ionizing radiation and related safety regulations must be tempered by actual accident experience. It is ridiculous to prevent workers in the nuclear industry from accumulating the same ionizing radiation exposure as do jet airplane air crew.

Concern about imagined extremely rare accident scenarios must be tempered by a design philosophy that sooner or later any system will fail and the consequences of that failure must be tolerable by the public.

Above all, government ministers must put real progress in mitigation of climate change ahead of other government priorities. If that means bankruptcy of uncooperative fossil fuel companies, so be it. They have already had fifty years to voluntarily invest in sustainable nuclear power but have failed to do so.

The NWMO must forget about permanent burial of used CANDU fuel.

31. Part 2 Appendix - Major Utilities:

The knee jerk response to climate change by politicians is to build more thermal neutron reactors. However, as shown in Part 1, thermal neutron reactors cannot sustainably prevent climate change.

A significant personnel training challenge facing major electricity utilities will be transitioning from thermal neutron reactors to Fast Neutron Reactors (FNRs). This transition is required to meet the need for enough economic, sustainable and dependable clean power to displace fossil fuels.

This fuel switch requires construction of an entire new fleet of FNRs.

The major electricity utilities, particularly Ontario Power Generation (OPG) and possibly Sask Power, have already been sucked into ongoing support of inefficient water-cooled Small Modular Reactors (SMRs). In part that situation is the fault of three decades of federal and provincial governments that squandered opportunity for FNR development and deployment.

32. Part 2 Appendix - Major Governmental Corruption

An unfortunate reality is that our present Canadian federal government is deeply corrupt. Present government policy is set by the fossil fuel industry, not by real climate mitigation considerations. In 2016, soon after being elected on a climate change mitigation platform, the federal cabinet committed Canadian taxpayers to funding a more than $30 billion expansion of the Trans-Mountain Oil Pipeline. That expansion has yet to earn a dime and will never meet climate change objectives. That $30 billion should have been applied to expansion of the CANDU reactor fleet.

During the same period (FY 2015/16 – FY 2023/24) the federal government failed to spend a budgeted $14.3 billion on climate change mitigation. (Ref: Corporate Knights, Climate Dollars: Federal Commitments and Expenditures, April 2024).

By far the largest source of clean energy available for climate change mitigation is Fast Neutron Reactors (FNRs), In the near term used CANDU fuel should be converted into FNR fuel via two steps known as TRU Concentration and Pyro-processing. However, in June 2023 the Canadian government refused to 50% fund TRU Concentration work by a multi-party team consisting of Xylene Power Ltd., FNR Power Ltd, Canadian Nuclear Laboratories and others.

Attached hereto is a copy of a letter from Natural Resources Canada to Xylene Power Ltd. in which Natural Resources Canada stated **"your project ….cannot be considered further for funding".**

Absent certain availability of FNR fuel and related supporting federal legislation it is impossible for the provinces or electricity utilities to finance engineering, construction and deployment of Fast Neutron Reactors (FNRs). However, FNRs provide the only means of sustainable climate change mitigation.

It is clear that, irrespective of climate benefits, the present federal government is refusing to spend money on nuclear projects that have the potential of making existing fossil fuel companies insolvent.

At this time it is clear that every person in the federal government who has supported funding of the Trans-Mountain Pipeline expansion or who has opposed reprocessing of used CANDU fuel to make FNR fuel needs to be terminated for cause.

The blunt reality is that if human life is to continue on planet Earth the Trans-Mountain Pipeline expansion can never operate as its proponents intended. Similarly, without FNR fuel there can be no FNRs, in which case **there will be runaway global warming.**

33. Part 2 Appendix – Refusal by Natural Resources Canada to fund work on TRU Concentration

Natural Resources Canada | Ressources naturelles Canada

June 30, 2023

Charles Rhodes
Xylene Power Ltd
Sharon, ON
L0G 1V0

Dear Charles Rhodes,

Subject: TRU CONCENTRATOR.

Thank you for submitting your Expression of Interest (EOI) in response to Natural Resources Canada's (NRCan) Enabling Small Modular Reactors (SMR) Program, to fund research on SMRs.

This was a highly competitive process, following a robust review process by a panel of technical experts. Applications were reviewed by an expert committee and ranked on a set of common criteria as outlined in the EOI template.

I regret to inform you that your project was not selected and cannot be considered further for funding.

If you would like more information, we can offer up to 15 minutes to discuss your application. To schedule a call, please respond to this notification with the subject line: "Debrief Request for TRU CONCENTRATOR."

Again, thank you for your time and effort in submitting your Expression of Interest. Should you have any questions, please connect with my staff by contacting: smr-prm@nrcan-rncan.gc.ca.

Yours sincerely,

Justin Hannah
Senior Director, Nuclear Energy Division
Nuclear Energy & Infrastructure Security Branch
Natural Resources Canada
580 Booth St
Ottawa K1A 0E4

Canada