Incentives for consideration of Carbide as candidate fuel for SFR

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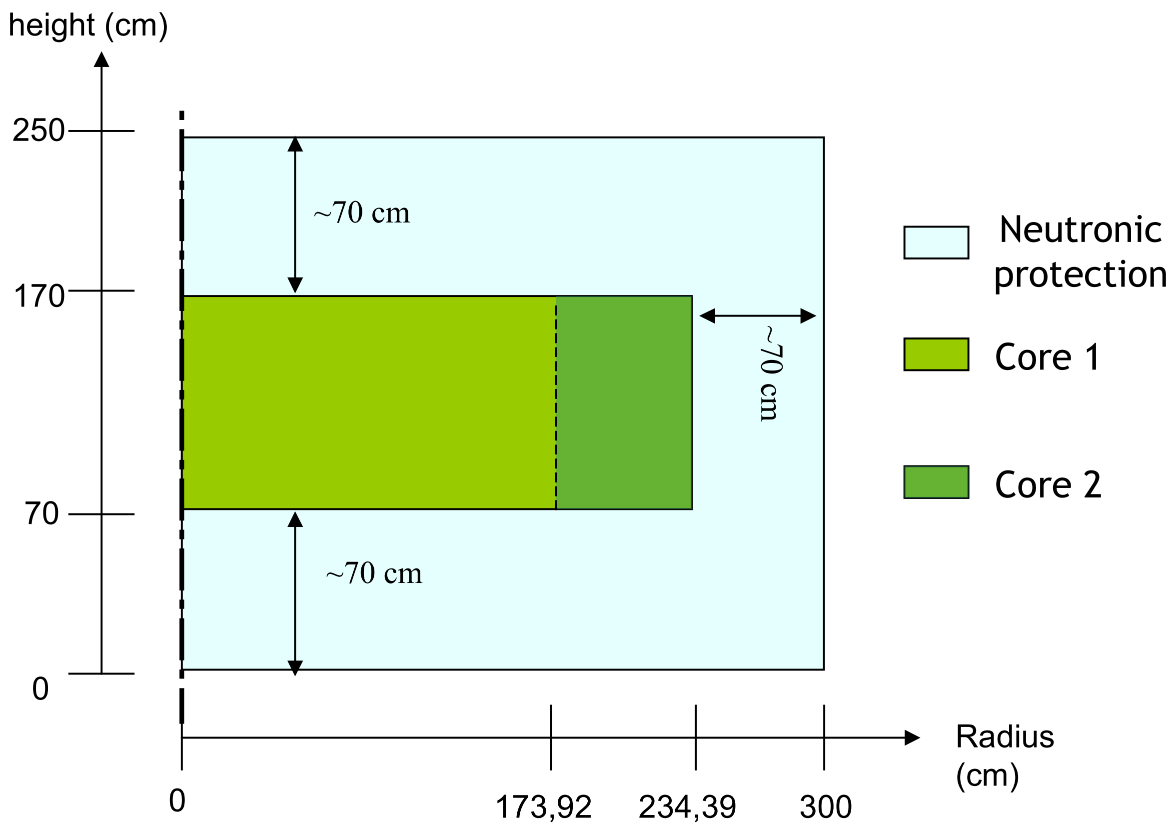
Neutronics considerations

- **Search for self-breeding** (natural ressources saving) without blankets (Prolif. Resistance)
  - Δ_{mass} Pu239 equivalent ≥ 0
  - mean Internal Breeding Ratio IBR ≥ 0
- **Sodium void effect and Void/Doppler ratio minimal** (safety concern)
  - Void/Doppler < 1 ?!
- *A parametric study was made in order to cope with the following difficulty:*
- How to reduce sodium void effect without reducing Doppler effect, while keeping the breeding gain ≥ 0
- **Parameters considered are:**
  - Geometry : H/D ratio, core volume, core radius,
  - Core composition : **type of fuel**, volume fractions of materials (fuel, sodium)
  - others : introduction of minor actinides (M.A.), moderator, sodium plenum…

Reference core for the parametric study

- Diffusion calculation on a (R,Z) geometry



- Core optimized for a fuel management by 1:5 with $\rho \approx 0$ at BOL (or EOL) Calculations made in the hypothesis of a management by whole, 200 dpaNRT at EOL.
- (the core is the core that achieved equibrium, i.e. at cycle nb 3) .

Reference core main characteristics

Thermal power	3600 MWth
Power density	209 MW/m^3
Core volume	17,259 m^3
Core height	1,000 m
Core radius	2,344 m
Ratio (height/ diamter)$_{core}$	0,21
Fuel	$(U,Pu)O_2$
Pu Isotopy (mass%)	Pu^{238} 1,7 Pu^{239} 58,1 Pu^{240} 22,3 Pu^{241} 11,3 Pu^{242} 5,4 Am^{241} 1,2
Pu equivalent content (volume %)	Zone Cœur 1 : 10,6 Zone Cœur 2 : 13,2 Moyenne cœur : 11,8
Core Composition (volume%)	46,6% fuel, 27,6% sodium, 18,4% steel, 7,4% void
Neutronic shield (volume %)	50% sodium, 50% steel
Core inlet tempertaure	395°C
Core outlet temperature	545°C
Fuel mean temperature	1227°C
Nominal clad temperature	633°C
T fuel melt (max Doppler effect)	2700°C

Safety parameters of the reference core

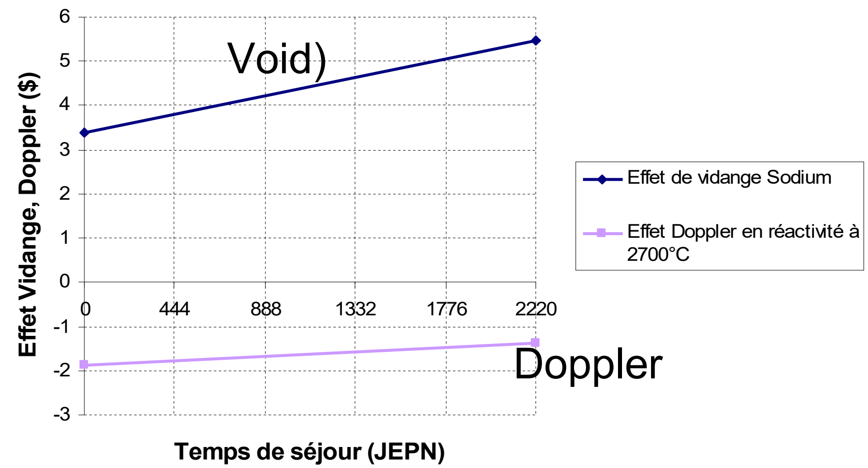
- Void effect is assessed as:

$\rho_{Na\ void} = \rho_{empty} - \rho_{nominal}$

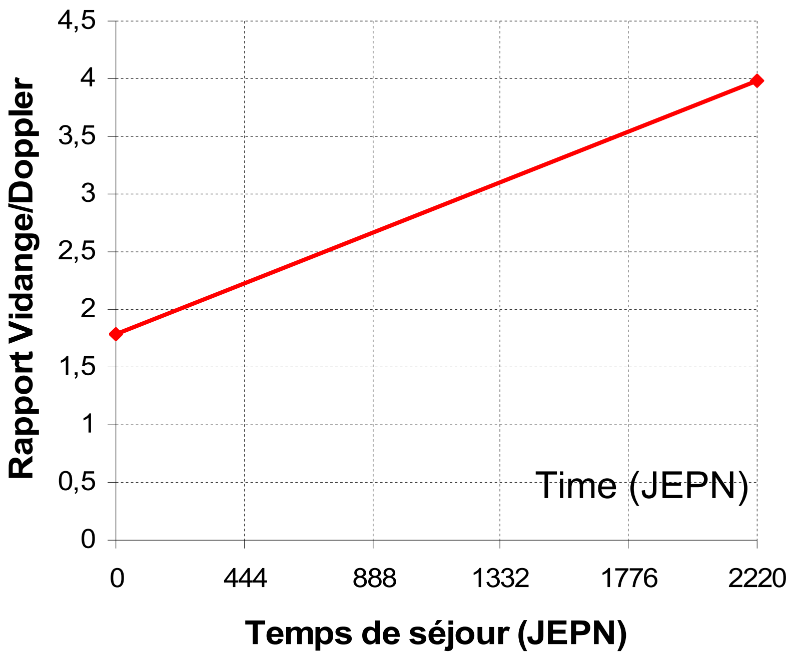
- Doppler effect is assessed as:

$\rho_{Doppler} = \rho_{fuel\ melt\ temp} - \rho_{nominal\ temp}$

- 1\$=β_{eff}=402 pcm DV et 344 pcm FV



Void/Doppler



» Void has a > 0 increasing trend.

» Doppler has a < 0 but decreasing trend

» Void / Doppler ratio is growing (shown as > 0) and reaches a value of 4 at EOL.

Optimisation of the ref core vs EFR

case	EFR		SFR "first version"	
THERMAL POWER	3600MWth		3600MWth	
LOWER AXIAL BREEDER THICKNESS (mm)	250		0	
FISSILE HEIGHT (mm)	1000		1000	
UPPER AXIAL BREEDER THICKNESS (mm)	150		0	
PELLET // HOLE DIAMETER (mm)	6,94 // 0		9,00 // 2,00	
PIN SPACER DIAMETER (mm)	1,14		1	
CORE PRESSURE DROP (bar)	5		2,5	
NOMINAL CLAD TEMPERATURE (°C)	630		633	
PEAK LINEAR POWER BOL (W/cm)	442		454	
FUEL	$(U,Pu)O_2$		$(U,Pu)O_2$	
CORE // UAB // LAB VOLUME (m^3)	11,9 // 3,3 // 4,8		17,25 // 0 // 0	
Height/Diameter // Core Radius (cm)	0,25 // 202,53		0,21 // 234,39	
POWER DENSITY (MW/m^3)	290		209	
CORE VOLUMIC FRACTION (%) Fuel	39,90		46,61	
sodium	35,10		27,61	
steel	25,00		18,39	
void	0,00		7,39	
Pu ENRICHMENT (%vol. fuel)	**19,21**		**11,94**	
FUEL RESIDENCE TIME (efpd)	5 x 340		5 x 444	
IBG	-0,126		0,040	
EBG	0,218			
AVERAGE TOTAL BREEDING GAIN	**0,092**		0,040	
SODIUM VOID EFFECT (BOL // EOL) (pcm)	1918	2907	1364	1962
($)	**5,26**	**8,72**	**3,39**	**5,70**
DOPPLER (BOL // EOL) (pcm)	-571	-444	**-760**	**-476**
SODIUM VOID / DOPPLER EFFECT (BOL // EOL)	-3,36	-6,55	-1,79	-4,12
DELAYED NEUTRONS (pcm)	365	333	402	344
AVERAGE BURNUP (GWd/t)	128		105	
PEAK DAMAGE DOSE (dpa NRT) (Fe)	197		200	

NO BREEDING BLANKET

GREATER PELLET

Lower Δ P : safety

Greater Core Volume core + breeders lower

Lower Power Density

Lower Pu enrichment

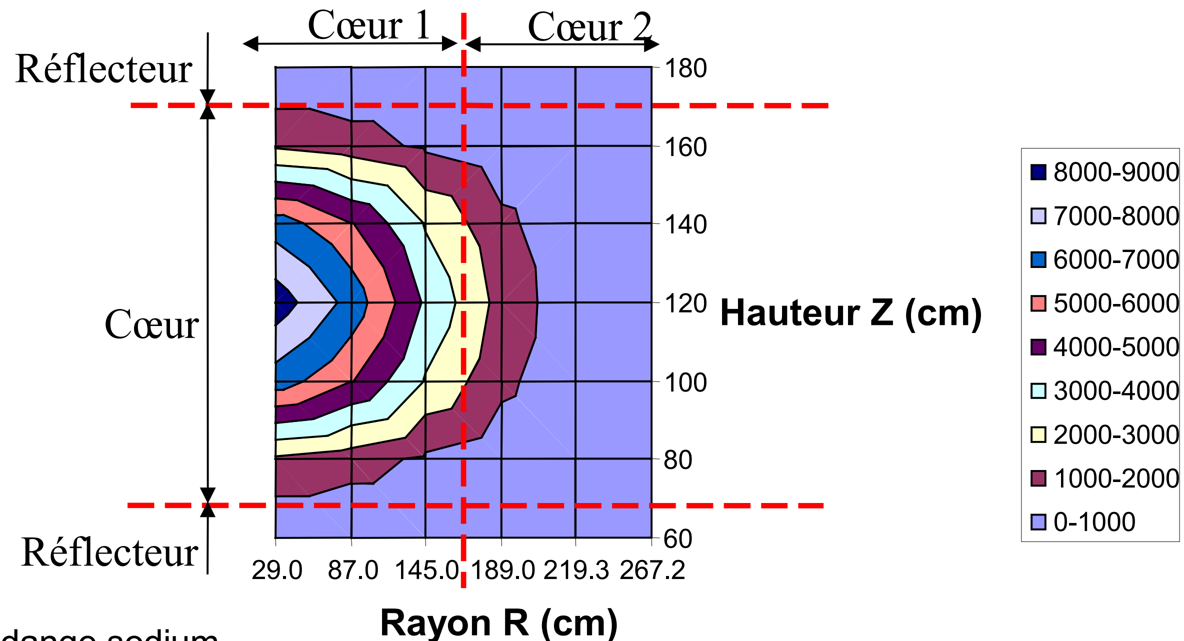
Lower TBG but without Breeding Blanket

Void Na / Doppler lower

Warning BU ≠ but same damages

Space distribution of void effect

Sodium void >0
At the core center



Distribution Spatiale de l'effet de vidange sodium (pcm)

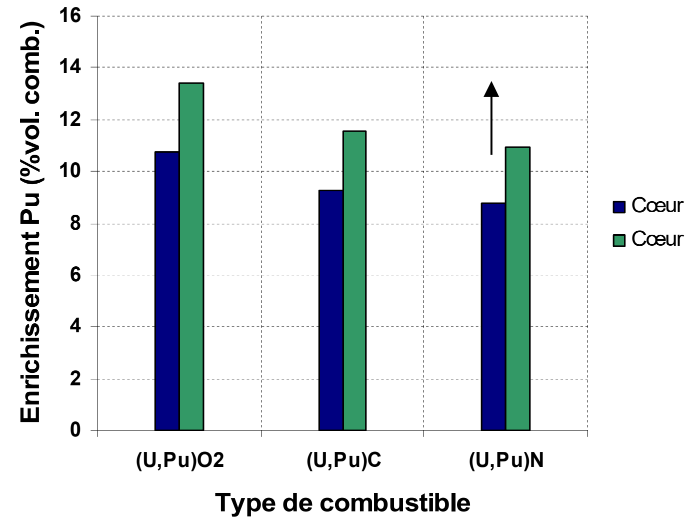
Hauteurs Z (cm)							
	250	0	0	0	0	0	0
	170	23	53	50	12	0	0
	150	80	186	178	52	10	0
	130	105	245	234	69	15	0
	110	80	186	178	52	10	0
	90	23	53	50	12	0	0
	70	0	0	0	0	0	0
	0	**58**	**116**	**173.9**	**204.16**	**234.39**	**300**
	Rayons R (cm)						
Par Ass		20	12	5	1	0	0

The central sub assembly has a void worth of 20 pcm
Whole core emptying has a1958 pcm void worth

Effect of the fuel material

- Temperatures used :

Fuel	$(U,Pu)O_2$	(U,Pu)C	$(U,Pu)N^{15}$
(g/cm^3)	10,57	11,56	12,16
Combustible (°C)	1227	887	887
Calcul Doppler (°C)	2700	2300	2000
Entrée cœur (°C)	395	395	395
Sortie cœur (°C)	545	545	545

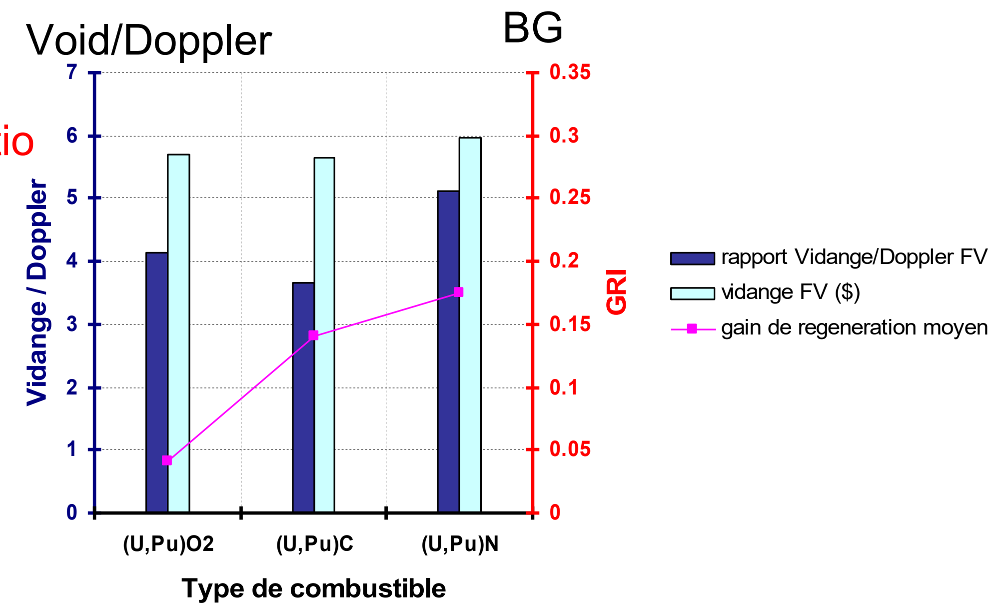


- Nota: nitride is supposed to be enriched in N^{15} at 100%

- Max temperatures for Doppler assessment:
  - Melting of oxide fuel.
  - Dissociation of carbide & nitride.
- No modification of vol. fractions steel / heavy atoms / structures
  - $\Rightarrow P_{LIN}$ unchanged
  - Pu enrichment is lesser with dense fuels

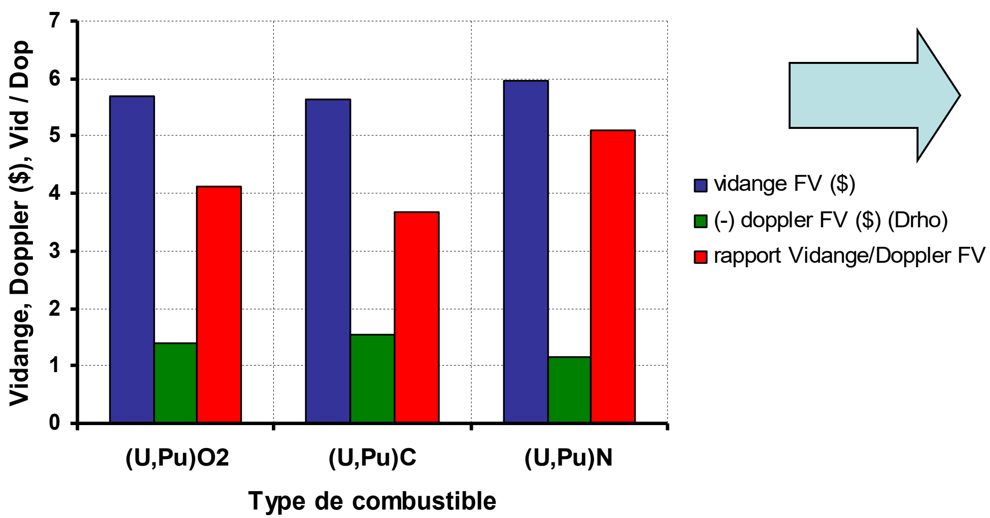
Effect of the fuel material

Dependance on the fuel material
is weak for safety parameters,
but significant on the Breeding ratio



(U,Pu)C looks a good compromise
for lower void/Doppler ratio and higher
Breeding ratio

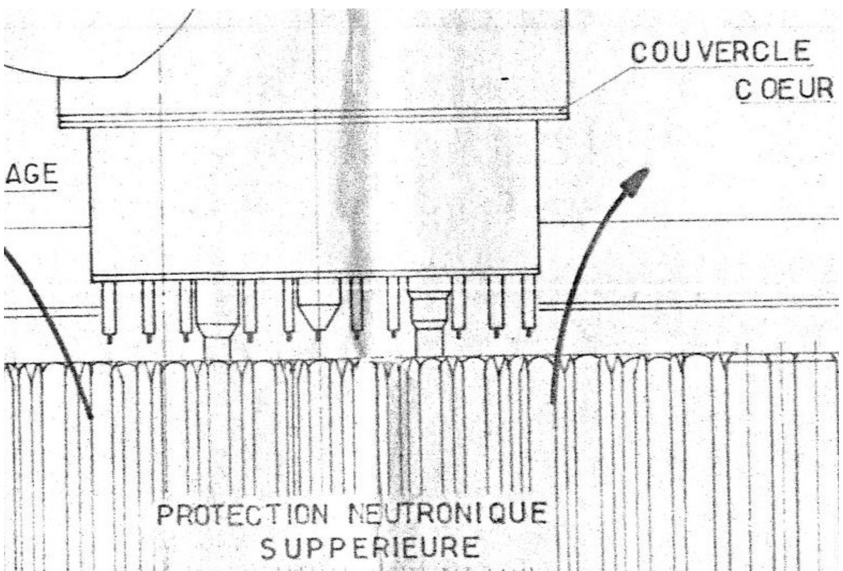
Nitride has the lesser Doppler in relation with
its temperature difference
Carbide has the weakest void worth and higher
Doppler



There is a good prospect for
enhancement of carbide core features
by enhancement of the fuel vol fraction
vs sodium, that will yield better BR
(more U8) and reduce void worth (less Na).
That is made possible due to good
thermal properties of carbide
Alternatively potential for increasing Pvol,
or designing a core with more neutrons leakage

Carbide for SFR, other arguments

- Reaction of oxide with Na producing $Na_3(U,Pu)O_4$ yields a temperature rise (bad conductivity of urano-plutonate & degradation of conductivity of the oxide due to decrease of O/M). Low density of uranoplutonate leads to swelling, liable to enhance the failure. The reaction will be enhanced if TNa is increased (that could be an objective for future SFR)
- Need for a performing monotoring but complicated and costly system:
  - DRG: clad failure detection
  - LRG: clad failure localisation



There is an incentive to study whether the carbide that is fully compatible with Sodium could allow for alleviated Core Monitoring System
(to have a management of clad failures close to LWRs procedures?:
Monitoring of FG (γ, definition of a threshold)
Shutdown according to α level

Carbide for SFR, other items

- Carbide: Margin to melt enhanced: $\lambda_{1000°C}$~19,6 W/m.°K instead of 2.9 for oxide, attractive possibility of Na gap
- Significant Experience under irradiation (FBTR India, 42MW, BR10 Russia, 10MW)
- Reprocessing: on-going studies with good prospect

- Drawbacks, open questions:
  - Pyrophoricity (manufacturing stage)
  - Swelling (low gaz release) & potential interaction at high BU
  - Carburization of the clad especially with Na gap
  - No experience with MA: loss of Am during carbothermic process?
- Nota: Carbide vs nitride:
  - Nitride needs a technology gap
    - -either for ^{14}C trapping in the waste
    - Or for low cost enrichment of natural nitrogen in 15 isotope

Severe accidents: drawback or open question?

- Studies by Sandia, ANL (75-85, in TREAT and APCR), Los Alamos (MS El-Genk):87, MFCI
- Energetic vapor explosion needs to gather a number of complex features never achieved in any experience at now,
- In existing tests pressure peaks obtained are higher with carbide than with oxide, but as to mechanical energy release, they are comparable
- Carbide strores less energy but releases it more quickly than oxide does
- Fresh carbide fuel submited to TOP actually exhibits large safety margings
- In case of core melt, nucleation model (with a criterion such as $T_{interface} > T_{spontaneous\ nucleation}$) predicts that interaction is possible with UC, not with UO2
- On such a basis licensing of carbide fuel looks impossible

Conclusion

- CEA intends to produce a study on the potential allowed by carbide fuel for SFR, dealing with:
  - Core design and safety
  - Core monitoring
  - In-core behaviour, that includes complete PIEs of carbides in the NIMPHE experiments achieved in Phenix
  - Cycle concerns

  - Results are proposed to be proposed to CEA's contributions in the concerned PMBs

  - If it is decided to go beyond, it is clear that a severe accidents program would have to be undertaken