PHYSOR-2004, - The Physics of Fuel Cycle and Advanced Nuclear System: Global Developments
Chicago, USA, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

Uncertainty Analysis and Optimization Studies on the Deep-Burner - Modular Helium Reactor (DB-MHR) for Actinide Incineration

Giovanni B. Bruna*[1], Rocco Labella[1], Christos Trakas[1],
Alan Baxter[2], Carmelo Rodriguez[2] and Francesco Venneri[3]
[1] *FRAMATOME-ANP, Tour AREVA, 92084 Paris La Défense Cedex - France*
[2] *General Atomics,P.O. BOX 85608, San Diego, CA - USA*
[3] *Los Alamos National Laboratory, Los Alamos, NM 87545 - USA*

The paper summarizes studies on the Deep-Burner - Modular Helium Reactor (DB-MHR) concept-design of General Atomics, which have been carried-out by FRAMATOME-ANP in the framework of a joint collaboration with General Atomics on the Reactor-Based Transmutation Program sponsored by the US Department of Energy. Feasibility and sensitivity studies as well as fuel-cycle studies performed both with probabilistic and deterministic methodology are presented. Emphasis is put here on most attractive physical and computational aspects of the concept.

Current investigations on the design uncertainties, the future search for ways to improve the transmutation worth in a double-stratum strategy, and the computational tools improvement are also presented.

KEYWORDS: Actinides, Incineration, Gas Turbine - Modular Helium Reactor (GT-MHR), Deep-Burner - Modular Helium Reactor (DB-MHR)

1. The Deep-Burner DB.MHR Concept

The MHR (Modular Helium Reactor) has been the subject of considerable design and analysis effort. Since 1995, the U.S. and Russia have cooperated on the design of a Gas Turbine - Modular Helium Reactor (GT-MHR) for the destruction of Weapons Grade (WG) Plutonium.

The reactor is capable of producing electric power at a very high thermal efficiency, while burning pure WG Plutonium to over 90% destruction levels. The same reactor can also be fueled with Uranium, or Uranium and Thorium instead of Plutonium, for strictly commercial use [1].

A variant of the concept, the Deep-Burner - Modular Helium Reactor (DB-MHR), has been proposed by General Atomics to fit sustainability objectives. It encompasses a wide capability to destroy by fission, and capture-followed-by-fission, transuranic waste discharged from LWR, with production of useful energy (electricity, hydrogen, process heat …) at high efficiency [1].

* Corresponding author, Tel. 33-1-47963943, E-mail: [giovanni.bruna@framatome-anp.com]

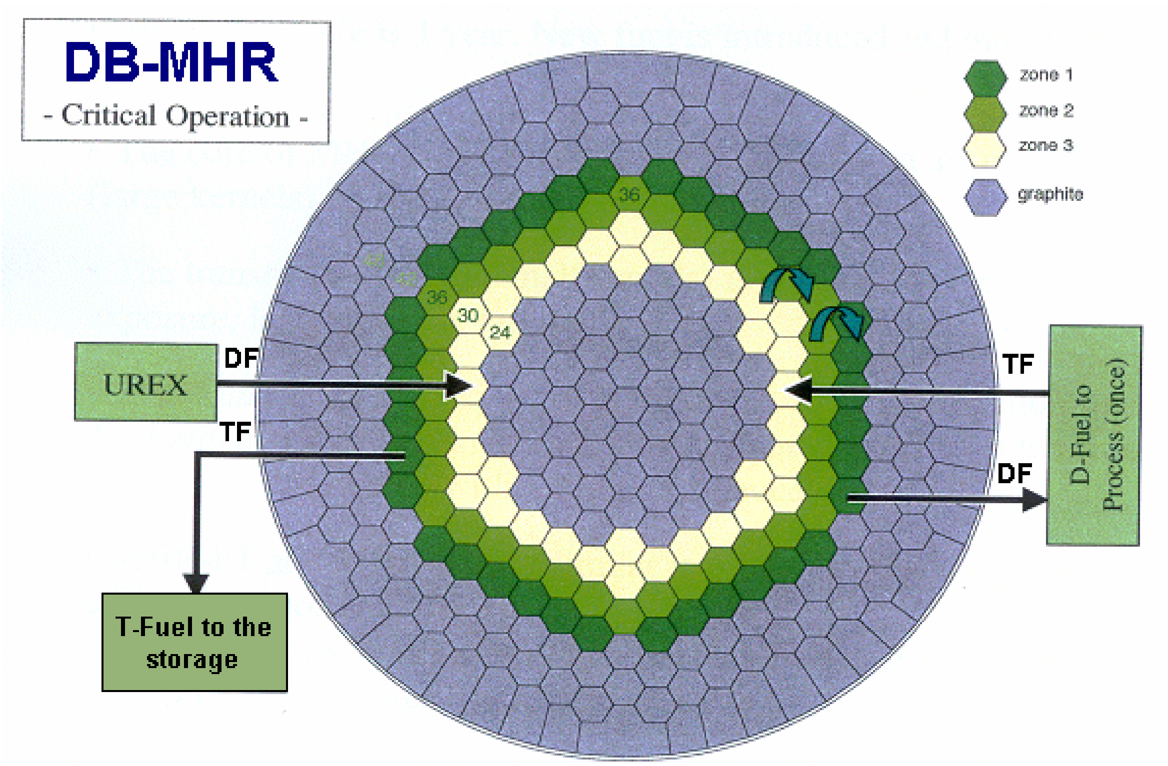

Fig. 1. The DB-MHR three-ring active core: Neutrons generated by **Driver Fuel** (DF) transmute the actinides in **Transmutation Fuel** (TF), which assures negative reactivity feedback and depletes resonance neutrons.

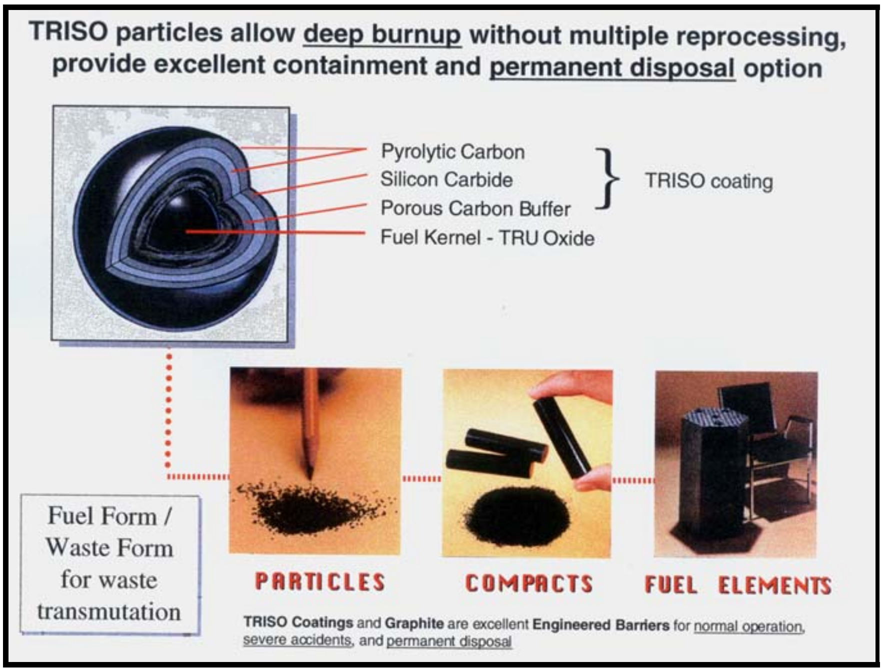

Fig. 2. The DB-MHR fuel

When used to destroy transuranics waste, the DB-MHR three-ring active core (Fig. 1) contains two different kinds of fuels:

- The Driver Fuel (DF), consisting of the Plutonium and Neptunium discharged from LWRs, and therefore mainly composed of fissionable materials and ^{240}Pu
- The Transmutation Fuel (TF), consisting of the minor actinides also discharged from LWRs plus the transuranics left in the DF after a complete irradiation cycle.

These fuels (Fig. 2) are packaged in ceramic-coated (TRISO) micro particles that are assembled in ceramic compacts. The compacts are, in turn, loaded and retained in heterogeneous graphite fuel elements (blocks), as shown in Figs. 2 and 3. [1].

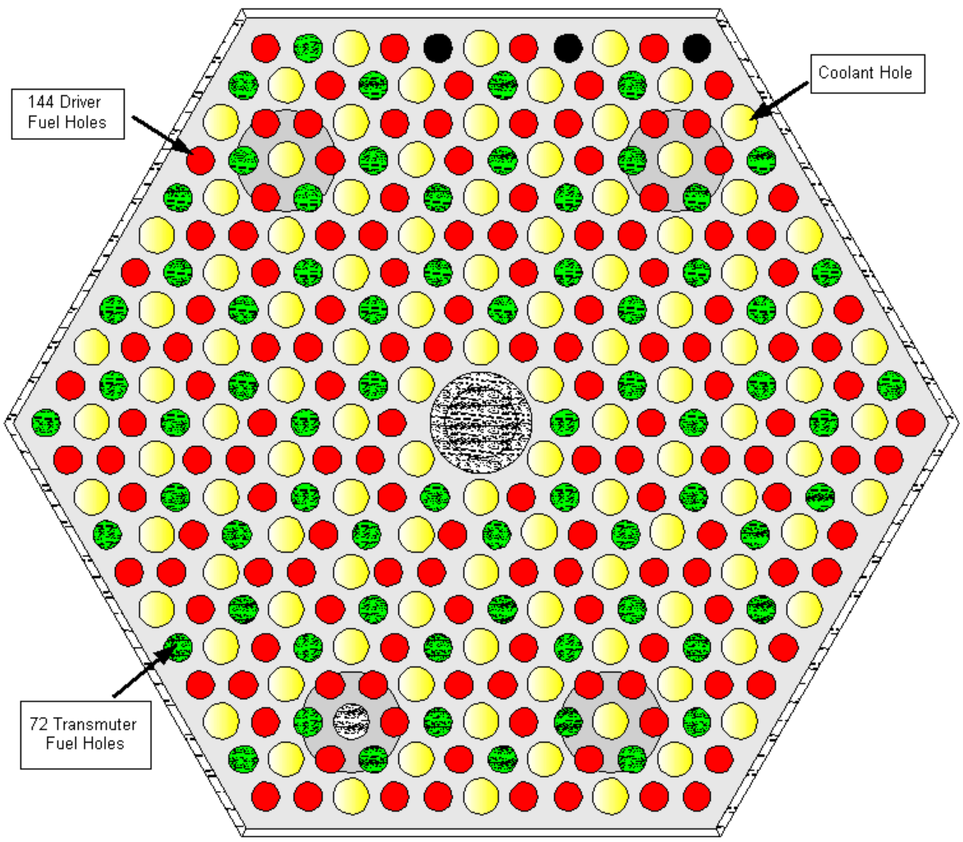

Fig. 3. The DB-MHR heterogeneous fuel element (block, assembly)

The work in Reactor-Based Transmutation Program was focused on defining the range of fuel cycles that would retain passive reactivity control, heat removal and fission containment features, and evaluating them from the standpoint of efficient use of resources, minimal waste generation, and attractive economics for application of interest, with emphasis on "deep-burn" features to reach high levels of internal conversion and burn without reprocessing.

Table 1. Basic parameters of the fuel micro- particles

Micro-particle fabrication features				
	DF		*TF*	
	Diameter (μ)	*Thickness (μ)*	*Diameter (μ)*	*Thickness (μ)*
Kernel($MO_{1.7}$)	*300*	*150*	*250*	*125*
Buffer	*600*	*150*	*450*	*100*
Inner Pyrolytic Carbon	*670*	*35*	*520*	*35*
Silicon Carbide	*740*	*35*	*590*	*35*
Outer Pyrolytic Carbon	*820*	*40*	*670*	*40*
Volume (CC)	*$2.887\ 10^{-4}$*		*$1.575\ 10^{-4}$*	
Average density (g/CC)	*2.23*		*2.09*	
Mass (g)	*$6.441\ 10^{-4}$*		*$3.293\ 10^{-4}$*	
Kernel density (g/CC)	*10.36*		*5.0*	

Note: $MO_{1.7}$ = 1.7 Oxygen atoms per heavy Metal atom. $MO_{1.7}$ is assumed to have a density of 10.36 g/cm^3. The transmuter kernel particle is 15 % in volume $MO_{1.7}$, and 85% in volume carbon at 1.74 g/cm^3. Binder, which holds the particles together in the compacts, is at 1.70 g/cm^3.

Table 2. Equilibrium reload characteristics.

Re-load parameters (equilibrium cycle)*		
	DF	***TF***
Number of blocs	*360*	
Number of compacts	*744480*	*372240*
N Compacts DF/ N Compacts TF	*2*	
Kernels Mass (Heavy Metal) (Kg)	*375*	*229*
Cycle length (EFPD)	*3 * 480*	*(3+3) * 480*
Transuranics waste incineration	*65 ± 5%*	
Criticality (K_{eff})	*1.00 ± 0.01*	

** DF Kernel Diameter 300μ (See Tab. 1)*

Based on this work, a reference DB-MHR conceptual design has been defined. It retains the major initial design features and constraints of GA's initial concept [1] on criticality, power release, power density and distribution. Its actinide transmutation performance (TRU, defined as the averaged total amount of actinides destroyed by fission over the heavy-metal DF charged per cycle) has been evaluated at 65% $\pm 5\%$ for a 3*480-day critical operation [2]. The main features of the model relative to the equilibrium re-load characteristics are summarized in Tables 1 and 2 above here.

2. DB-MHR Physics

The very gradual moderation of neutrons in graphite and the high temperature of DB-MHR, which generate a quite flat energy spectrum, and the energy dependence of actinide resonances in the epi-thermal region provide the main neutron-features of the DB-MHR for transuranics waste destruction.

Captures being, on the average, higher than fissions at epi-thermal energy, the non-fissile actinides are very effective sinks for neutrons slowing-down in the graphite and, when large amounts of them are present in the core, they temper the chain reaction allowing the fuel to burn-out slowly and more efficiently. Moreover, the ^{240}Pu, a strong absorber, transmutes gradually to ^{241}Pu, a fissile, and contributes to the increase of the fuel life-time. In this way, it helps in sustaining chain reaction. Neutron captures in this energy range also provide a strong negative reactivity feedback effect as the core temperature increases, for example during a power excursion, thus ensuring safe reactor operation. After transmutation by capture and radioactive decay within the nuclide chain, actinides eventually undergo fission and disappear to generate Fission Products (FP).

Therefore, the cycle integrated fission rate (which, neglecting second order spectral effects, is roughly proportional to the mass of actinides, the neutron flux and time via the cycle-length) is a fundamental parameter for measuring the transmutation efficiency of the system. Moreover, the cycle length, which is related to criticality through the cycle reactivity profile, is a complex function of three main free variables:

- The reloading mass, which acts on absolute criticality through the cumulative fission rate,
- The internal (within the assembly) and the overall core moderation ratio, which act on criticality through the neutron spectrum,
- The spatial self-shielding of the fuel micro-particles, which regulates the fuel consumption through the internal conversion ratio and the absorption rate.

Objectives of maximizing the actinide destruction rate within the TF and increasing ^{240}Pu self-shielding to extend critical operation lead the design of the fuel particles in opposite directions:

- The first one can be met through a reduction of the TF micro-particle kernel size,
- The second through an increase of the kernel diameter of DF.

A compromise between these two contrasting needs could be found through an adjustment of the core moderation ratio.

A heuristic proportionality formula holds within the explored range of DF diameters between the transuranics waste destruction and the relative variation of the fuel mass (for a given moderator mass).

Accordingly, the main parameters for actinide-incineration optimization in DB-MHR are:

- The core coupling and the neutron spectrum, which are both very sensitive to the moderator to fuel ratio and the graphite capture rate,
- The local neutron spectrum (through the modification of the graphite density inside the compact and or the optimization of the micro-particle size).

Because of the large migration area of neutrons, which cancels out the effects of local heterogeneity, macroscopic parameters are generally most effective than local ones in such cores.

3. DB-MHR Studies and Results

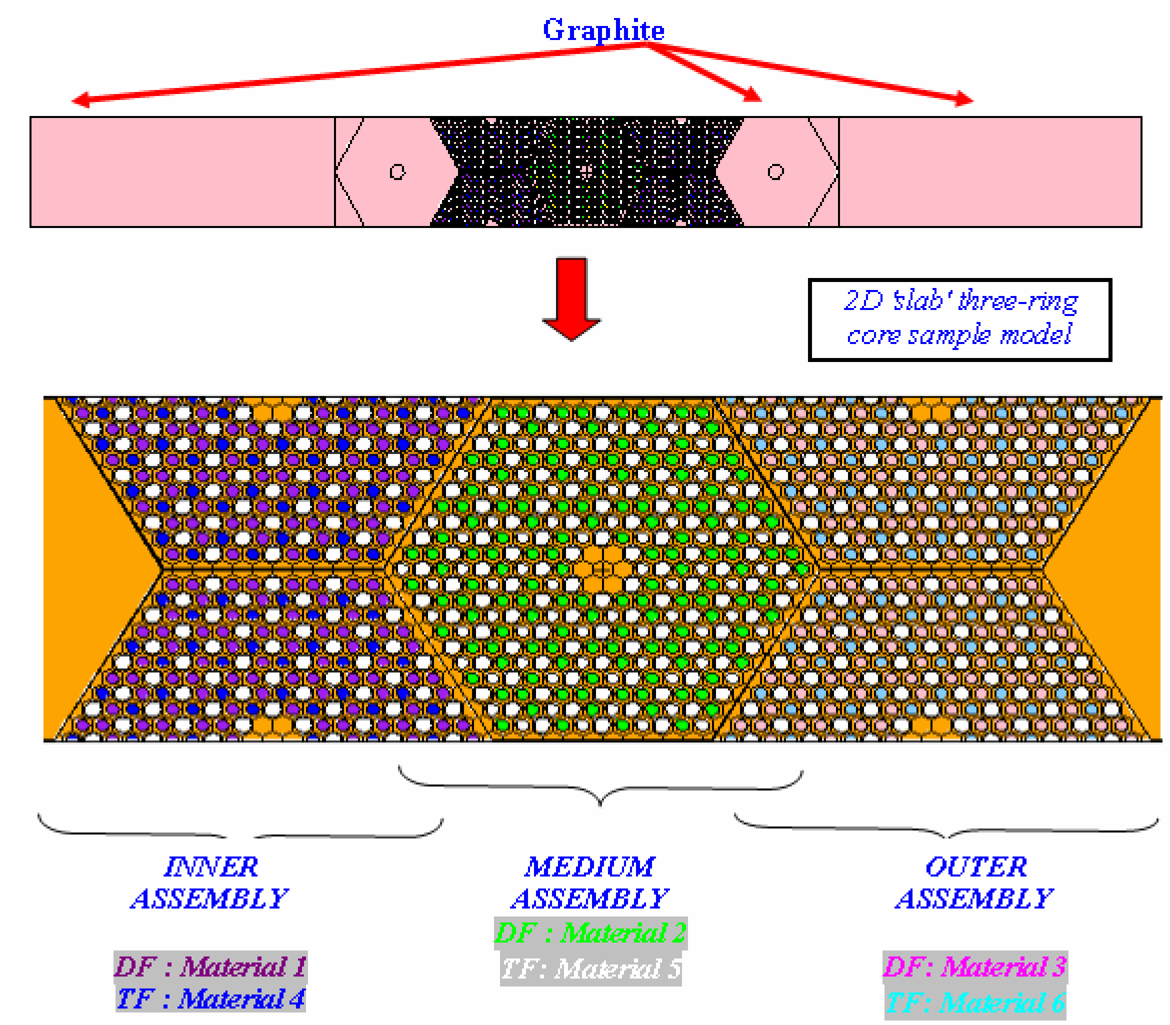

Fig. 4: 2D slab core model with three same volume core regions and equivalent reflector regions on the right and left side

A survey of the DB-MHR conceptual design studies, carried-out by FRAMATOME-ANP and General Atomics is presented in [2]. The paper also summarizes the parametrical investigations aimed to mastering the local and macroscopic parameters governing the system actinide transmutation performance and presents transition to the equilibrium-cycle studies.

The present paper is mainly aimed at investigating fundamental issues, such as the sensitivity of the transmutation efficiency to the micro-particle mass and size, and the moderator effect on the neutron spectrum in the resonance region. The main sources of uncertainty on transuranics waste incineration and system stability are analyzed too. The paper eventually suggests ways to increasing the DB-MHR incinerating capacity by adjusting the core coupling, tuning of the neutron spectrum and modifying the fuel re-loading strategies.

Computations were manly performed on a simplified 2D-slab model of the core (see Fig. 4) benchmarked on a 3D full core model on main reactor parameters. The probabilistic MCNP-MONTEBURS-ORIGEN chain [3] was primarily used.

Since the current parallel version of the computational scheme was unavailable when the study was carried-out, the computation running-time turned out a major parameter of the study. Therefore, an investigation was carried-out to minimize run-time without affecting the precision of the major design integral parameters. The main calculation assumptions and options, such as the statistical precision of the MCNP runs, the number of time-steps in the cycle, the number of regions allowed to burn-out independently, the accuracy of the power calculation (accounting in a simplified way for contribution from radioactive capture, actinide and fission-products β and γ energy deposition) and the MCNP-MONTEBURNS coupling through isotopic composition were evaluated and validated.

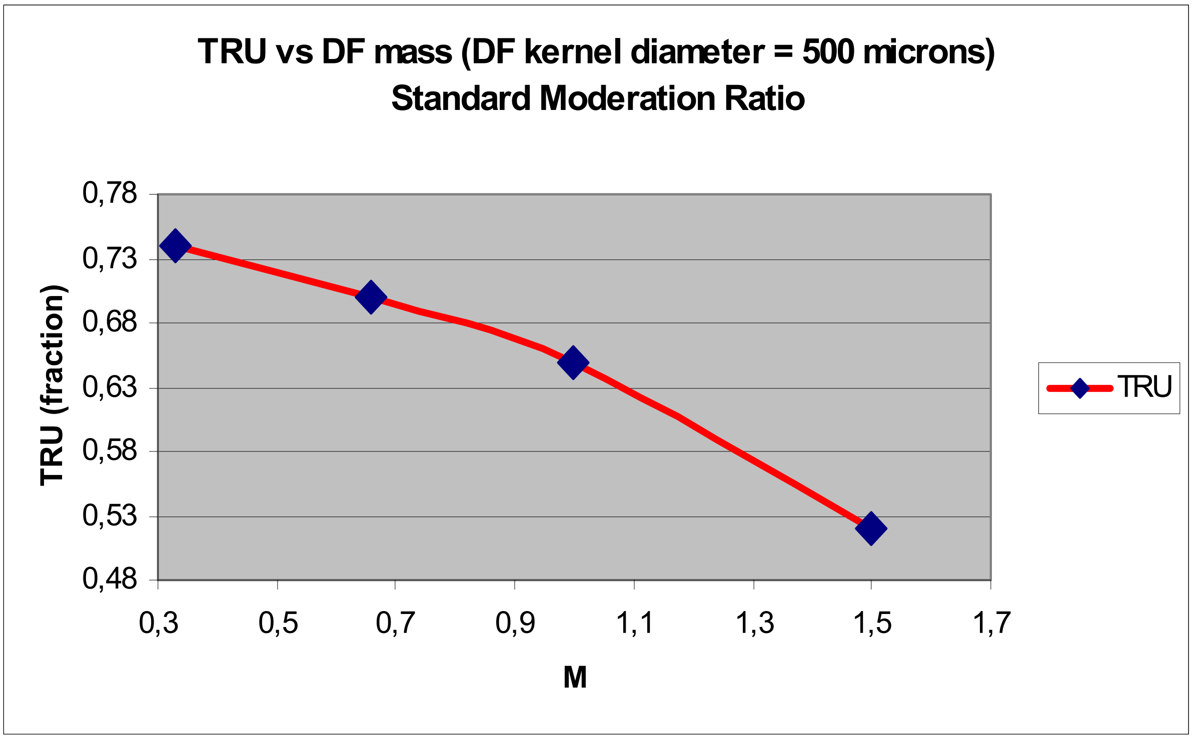

Fig. 5 Sensitivity of TRU to DF mass (DF kernel diameter 500μ)

Figs 5 to 7 and table 3 summarize some results of the above mentioned studies. It is to be noticed that, among the 5 cycles in Figs. 6 and 7, only the very last one is representative of pseudo-equilibrium, the others simulating the transition to equilibrium from all-fresh-fuel conditions.

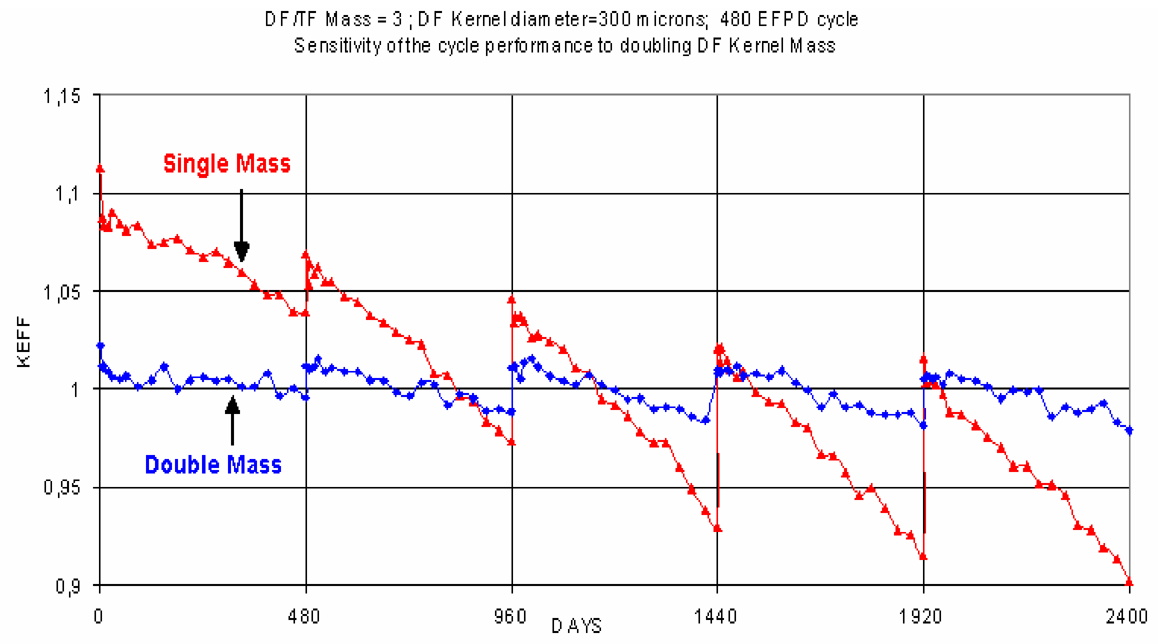

Fig. 6. Sensitivity of the cycle performance to de DF kernel mass.

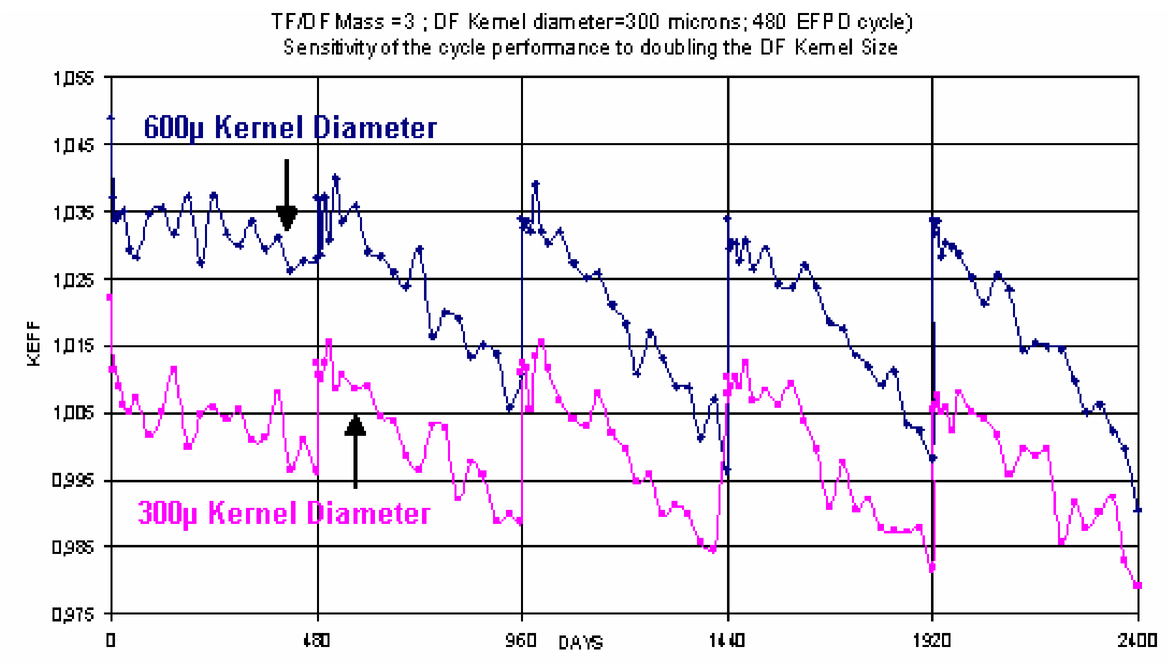

Fig. 7. Sensitivity of the cycle performance to the doubling of the DF kernel size.

Infinite medium assembly configuration benchmarking with the deterministic CEA transport assembly code APOLLO-2 [4] provided a valuable complementary support, and contributed to performing preliminary uncertainty estimation.

Table 3. Sensitivity of transuranics waste incineration to DF mass and size (standard fuel mass, M_0).

End-of-cycle Keff Equilibrium cycle	*DF / TF*	*DF mass reloaded per /cycle (Kg)*	*DF diameter*	*Transuranics waste incineration rate (%)*
0.90 (480 fpd§)	*3.0**	*375*	*300 μ*	*0.70*
0.98 (480 fpd§)	*3.0**	*750*	*300 μ*	*< 0.50*
1.00 (<350 fpd§)	*1.64***	*125*	*500 μ*	*0.74*
1.00 (<480 fpd§)	*1.64***	*250*	*500 μ*	*0.70*
1.00 (480 fpd§)	***1.64*****	***375***	***500 μ***	***0.65***
1.00 (> 480 fpd§)	*1.64***	*563*	*500 μ*	*0.52*

§ *fpd = Full-Power Days*
* *This DF / TF ratio gives an unrealistic end-of-cycle under-critical condition*
** *Realistic TF vector after transition to equilibrium (6 cycles)*

4. Elements on DB-MHR Stability

Major contributions to the DB-MHR core stability come from:

- the fast-acting temperature effect of the fuel (Doppler effect of even Pu isotopes and minor actinides),
- the average middle term temperature effect of the graphite moderator (sensitivity of the moderator slowing-down efficiency to the neutron up-scattering),
- the effect of the axial profile of the temperature (variation of the axial temperature profile in case of reactivity driven transients).

Doppler and graphite temperature effects have been widely investigated in the reference case (standard fuel mass, M_0) in the 2D 'slab' configuration.

The moderator temperature effect is the major stability parameter of such cores in the middle long term. In presence of fast temperature changes (reactivity driven accidents) the Doppler coefficient gives a feedback of about -1.5 pcm/C° [1 pcm = 1.0 10^{-5} $\frac{\delta k}{k}$] quite lower than the standard -3.0 pcm/C° observed in conventional PWRs, and the graphite moderator effect is up to -4.5 pcm/C°. In a first approximation, these values remain constant throughout the cycle, but moderator temperature coefficient shows-up very sensitive to the temperature range.

The effect of the axial profile of temperature has not yet been investigated, because it needs knowledge of a fine axial burn-up profile, which can only be computed in a 3D model. It is part of the work-program for further activity.

For the sake of completeness, it is to be noticed [5] that the system possesses a very large inertia during reactivity driven transients, owing to a relatively long prompt neutron lifetime which helps to offset the effect of the low delayed neutron fraction (typical values of the prompt-neutron lifetime lay in the range 400 to 700 μsec, depending on the design features, the delayed neutrons fraction being in the range 250 – 300 pcm [0.25% - 0.30% $\frac{\delta k}{k}$]].

5. Uncertainty analysis

The uncertainty on transuranics waste destruction is presently estimated at $\pm 5\%$, and on criticality throughout the cycle at 1000 pcm [$\pm 1.0\% \frac{\delta k}{k}$]. Further investigation is needed to reduce the uncertainty on the transmutation worth to a target figure of $\pm 3\%$ on transuranics waste destruction and to $\pm 0.5\% \frac{\delta k}{k}$ on cycle reactivity profile. These values are in agreement with current Plutonium fueled PWR experience.

The main sources of uncertainty on TRU are:

- The cross-sections, through reaction-rates, reactivity and power,
- The fuel depletion process, trough several parameters such as the flux level and profile and nuclear data, such as the fission yields and the branching rations in the actinide chains,
- The amount of energy released by fission, which accounts for direct and indirect sources (average kinetic energy of fission fragments, neutron capture, fuel radioactive decay),
- The feed-back of graphite, through its capture and up-scattering sensitivity to the temperature.

Errors come also from geometry and computational procedure:

- The effects on reactivity and power of the stochastic distribution of micro-particles inside the compacts,
- The geometry description simplifications,
- The computation options, such as:
    - The statistical precision of probabilistic calculations
    - The number of time-steps in burn-up calculation,
    - The number of regions allowed burning-out independently.

Cross-sections are potentially a major source of uncertainty. According to the lack of operational experience for these systems, only a theoretical analysis can help in making a preliminary evaluation:

Owing to its quite strong temperature feedback, graphite shows-up a major source of uncertainty in DB-MHR studies, although investigations mentioned in [6] show that, for a UOX fuel, graphite reaction-rates (including capture, down-scattering and up-scattering) are quite accurate within a wide range of neutron spectra. Cross-sections of major Pu isotopes are quite well known too. They generate a minor uncertainty on reactivity only, that becomes a systematic over-prediction of about + 0.30% $\frac{\delta k}{k}$ in very thermalized systems, quite afar for DB-MHR. Cross-sections of minor actinides are generally poorly known. In the literature, discrepancies up to 20% in capture cross-sections of such isotopes are observed, which can generate in time a very large dispersion in their concentrations, but only a negligible impact on reactivity owing to their small amounts relative to major contributors and their low thermal and epi-thermal cross-sections.

The fission yields and the branching ratios are correct on the average so that no systematic effect has been observed for Fission Products. Only a slight over-evaluation was noticed for ^{239}Pu and ^{240}Pu production, as a consequence of a small over-capture (over-conversion) of ^{238}U in the epi-thermal region. DB-MHR DF and TF fuel being ^{238}U free, one can assume that the triplet [^{239}Pu, ^{240}Pu and ^{241}Pu] overall production is quite correct._ On the average, all contributions from systematic errors approximately cancel out, which allows ignoring the systematic component of uncertainty.

As regards the statistical component, it was evaluated at $\pm 0.5\% \frac{\delta k}{k}$ (500 pcm) maximum for a fresh fuel, which means about ± 200 pcm on the average equilibrium cycle core.

Uncertainty figures are far less than the design uncertainty of $\pm 1.0\% \frac{\delta k}{k}$ on criticality and $\pm$ *5%* on transuranics waste destruction, conventionally agreed between FRAMATOME-ANP and G.A.

6. Further improvements and developments

The initial design and layout of the DB-MHR was closely based on the commercial GT-MHR design [1 and 7]. However, studies presented here have shown that significant improvements of its capability to burn transuranics out could be achieved through further changes in the design. These changes include adjustments of the graphite moderation worth and absorption rate to increase core coupling. This could be obtained for example, by withdrawing several graphite elements in the inner reflector, or by modifying the moderator density.

Design modifications could also include changes to the fuel loading strategy, for example, by adoption of a centre-in-out strategy (instead of the current centre-out-in version). This should give two main advantages:

- Improving the flattening of the power within the core,
- Enlarging the domain allowed for DF mass optimization.

Further improvements could be achieved trough a fine control of the axial power shape.

Such options will be investigated in a next phase of the study, including verification of the overall design concept consistency, and evaluation of core cooling and mechanical stability, mainly with respect to the very sensitive aspects of the resistance of graphite to irradiation, and the stability of its mechanical properties, (graphite activation is minimal, making it Class C low level waste).

Regarding computational aspects, two main R & D development paths are now considered for the near future:

- Adoption and implementation of a highly parallelized version of the probabilistic chain, with capability to couple several processors,
- Development of a core 3D design core chain.

7. Conclusion

The paper summarizes studies on the DB-MHR concept-design carried-out jointly by FRAMATOME-ANP, and General Atomics in the framework of a joint collaboration on the Reactor-Based Transmutation Program. Preliminary design studies as well as sensitivity studies and fuel-cycle studies were performed.

Emphasis is put here on the transmutation performances of the reference model eventually defined after several iterations, which retains the main original design features and constraints of the GA's initial DB-MHR concept. Its actinide transmutation worth is evaluated at about $65\% \pm 5\%$, a figure in itself quite attractive, which could be increased to about 75% with improvements on particle size and mass, core moderation worth and coupling and re-loading strategy. Moreover, the spent fuel composition should easily allow further transmutation with the addition of an ADS (Accelerator Driven System), with expected gains of 15% or more.

References

1) F. Venneri et al. "Deep Burn Transmutation. A Practical Approach to the Destruction of Nuclear Waste in the Context of Nuclear Sustainability", DOE report FDO-E00-N-TRT-X-000132, December 19, 2001;
2) G. B. Bruna, R. Labella, C. Trakas, A. Baxter, C. Rodriguez, F. Venneri and C. Poinot, "Deep-Burner DB.MHR: Physics and Computation", Proceedings of the International Conference on Supercomputing in Nuclear Applications SNA '2003, Paris, September 2003;
3) D.I. Poston and H.R. Trellue, "User's Manual, Version 2.0 for Monteburns, Version 1.0", sept. 1999, LA-UR-99-4999;
4) F. Damian, X. Rapsaet, F. Moreau, "Code and Methods Improvement in HTGR at CEA", Proceedings of the International Conference on the New Frontiers of Nuclear Technology, PHYSOR 2002, Seoul, Korea, October 2002;
5) G.B. Bruna, "Le projet GT-MHR : un cas de résurgence des réacteurs à gaz", Proceedings of "Journée de la Société Royale Belge des Électriciens", Brussels, April 2003;
6) C. Trakas and L. Daudin, " Benchmarking of MONTEBURNS against measurements on irradiated UOX and MOX fuels" Proceedings of this PHYSOR 2004 Meeting,
7) C. Rodriguez et al., "MHR Reactor-Based Waste Transmutation: Economics, Safety and Security Assessments", General Atomics Report GA-501-0-TRT-000186, GA-A24181, Rev A, issued November, 25, 2002.