SCENARIOS FOR WASTE MANAGEMENT INVOLVING INNOVATIVE SYSTEMS (ADS)

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ABSTRACT

The global performance of reactor park scenarios based on innovative systems (Accelerator-Driven Systems, ADS) for transmutation is studied, based either on equilibrium recycling states or on high burn-up systems. The results of these first studies are preliminary but allow to assess the main parameters of the fuel cycle (inventories, mass balances, mass flows...), to evaluate the specific contributions of ADS on the main scenario parameters, and to compare subcritical systems to critical ones.

Keywords : transmutation, waste management, ADS

1. INTRODUCTION

Innovative fission systems able to burn efficiently plutonium and/or minor actinides (MAs) are investigated here. There are two basic ways to achieve a massive transmutation : either to perform multiple irradiation runs with a limited burn-up for each run, and reprocessing, topping and re-fabrication between each run (this will be called multiple recycling) or to perform a single irradiation run with a very high burn-up, in order to limit as much as possible the amounts to be reprocessed and fabricated into fuel elements (this will be called once-through recycling).

In the first case, we shall study "equilibrium" scenarios, i.e. assess the asymptotic proportions of the different reactor types in the reactor fleet, the asymptotic composition in the burner reactors and in the waste stream (a given loss level at reprocessing being assumed). In the second case, the achievable burn-up will be investigated.

What motivates the use of accelerator-driven systems (ADS) is either that a fuel with large amounts of degraded plutonium or minor actinides inside is characterized by bad reactivity coefficients (e.g. void coefficient, Doppler coefficient, delayed neutron fraction), and in this case the subcriticality brings substantial margins for a safer core operation [1], or even to simply make possible the core operation if the multiplicative factor is lower than one, e.g. to reach high fuel burn-ups.

2. CLOSED SCENARIOS : EQUILIBRIUM

We investigate here a closed cycle, that is a multiple recycling of actinides. In that way, only reprocessing losses go to the waste. These losses are assumed here to be 0.1% for all actinides. The core concepts studied are dedicated to the transmutation of actinides, i.e. their fuel is made only of plutonium and minor actinides, and they can be critical or sub-critical reactors (ADS).

In the so-called **"double strata"** scenarios, a first "stratum" of reactors is used for plutonium recycling (with neptunium), and a second "stratum" of reactors is dedicated to burn the other minor actinides, i.e. Am and Cm. The **"double component"** scenarios involve two types of reactors : standard reactors to produce electricity, based on PWR and uranium fuel, and innovative reactors burning Pu and MA together. In both cases, the burner reactor compositions are given at equilibrium, i.e. at the asymptotic regime when isotopic compositions are stabilised from a loading to the next.

The innovative concepts used to compare critical reactor and sub-critical reactors (ADS) are based on fast reactors using different coolant technologies: sodium (Na), lead or lead-bismuth (Pb, Pb/Bi) or gas (He). The critical cores for MA transmutation in double strata scenarios cooled by heavy metal are small units (150 MWth). The constraint on size is due to reactivity coefficients strongly affected by the large MA fraction in the fuel (see table 2) : the small size limits this impact. The ADS systems are medium size (1500 MWth) for any kind of scenarios, and sometimes "twin" ADS with respect to critical cores (i.e. same core volume and power) are studied in order to assess the difference due to subcriticality alone.

All calculations were performed using the ERANOS neutronic code system [2], with nuclear data based of JEF2 evaluations, adjusted on the major nuclides (main U, Pu, Fe, Cr, Ni isotopes, on O and Na).

2.1. Double strata scenarios

The "first stratum" is made of UOX PWRs and standard, EFR type, sodium-cooled fast reactors (FR) ; the PWRs feeding the FRs with their output plutonium. The second stratum is made of MA burners fed by the MA output of both PWRs and FRs, and possibly with some amount of plutonium being drawn from the Pu stream directed to the fast reactors, in order to support the reactivity level if needed. The asymptotic composition for the MA burner fuel results in a non-negligible plutonium content due to both the Pu feed (if any) and the transmutation of minor actinides (mainly captures on Np-237, capture + decay on Am241, and decay of Cm-244): see table 3 for the Pu content in the fuel. This plutonium is characterised by a very degraded isotopic composition, i.e. high content in even Pu isotopes: Pu-238 and Pu-242 (capture + decay on Am241) and Pu-240 (decay of Cm-244).

Table 1 gives some general data about the double strata cores. The main assumptions are on core power (global and specific) and fuel residence time. The low power for liquid metal cooled critical cores and their associated twin ADS is motivated by reactivity coefficient mitigation; it is worth noting then that the critical core contain some amount of hydrogenated moderator such as ZrH_x (a volume fraction roughly 5%) in order to reduce the coolant void reactivity and increase the Doppler feedback, and that the particle fuel for the gas-cooled reactors is placed within graphite-based subassemblies that provide some moderation as well. Residence times are assumed to lie between 3 and 5 calendar years. The fuel volume fraction results directly from the subassembly geometry for the critical cores. It was adjusted for ADS in order to obtain the prescribed reactivity level (k=0.98 at beginning of cycle): some dilution of the fuel with an inert matrix is then assumed.

Core type	Critical			"Twin" ADS			ADS		
Coolant	Na	Pb	He	Na	Pb	He	Na	Pb	He
Core power (MW_{th})	156	138	1000	156	138	1000	1500	1500	1500
Fuel volume fract. (%)	22.7	22.0	14.4	22.7	22.0	18.2	14.4	11.9	15.4
Actinide load (kg)	1267	1116	3336	1378	1213	3497	6376	5422	4798
Fuel resid. time (efpd)	1500	1500	900	1500	1500	900	1500	1500	900
Avg. power (W/cm^3)	274	243	441	276	244	442	406	406	407
Average BU (%)	18.3	18.3	26.7	17.0	17.0	25.5	34.6	40.4	27.8

Table 1 — General data for double strata cores

The main reactivity coefficients are given in table 2. This table shows that with a degraded Pu + MA fuel composition, the coolant void reactivity is high, even for very small liquid metal cooled cores; the absolute value of the Doppler constant is low despite the presence of moderator; and the delayed neutron fraction is very small. In order to have a reference for comparisons, typical values for a standard LMFBR core, such as Super Phénix or EFR are approximately 2200 pcm foe the sodium void reactivity, -800 pcm for the Doppler constant, and 360 pcm for the delayed neutron fraction. An advantage of ADS is to be much better able to cope with very the poor reactivity coefficients due to Pu+MA fuel than their critical counter parts.

Core type	Critical			"Twin" ADS			ADS		
Coolant	Na	Pb	He	Na	Pb	He	Na	Pb	He
$\Delta\rho_{coolant}$ (pcm)	2060	1290	—	2540	2950	—	4360	5440	—
$K_{Doppler}$ (pcm)	-211	-181	-253	-178	-119	-311	-422	-393	-485
β_{eff} (pcm)	162	155	148	213	142	121	121	140	133

Table 2 — Reactivity coefficients for double strata cores

Table 3 shows how the plutonium content in the fuel, the reactivity loss, and the accelerator requirements (intensity, fraction of the gross electrical power of the ADS devoted to feed the accelerator) are correlated. The lower reactivity level for ADS with respect to critical reactors allows to decrease the plutonium content; this reduction is amplified by a size effect (leakage reduction for larger cores). The larger size should also lead to a reduction of the reactivity loss, but this effect is somewhat offset by the increase in specific power (for the liquid metal cooled cores). The reactivity evolution vs. time, made of an increase at low burn-ups followed by a decrease may lead to very small accelerator requirements for the equilibrium batch.

Core type	Critical			"Twin" ADS			ADS		
Coolant	Na	Pb	He	Na	Pb	He	Na	Pb	He
Pu/(Pu+MA) (w%)	55.5	48.5	38.6	44.0	39.2	36.0	32.5	29.7	37.7
$\Delta\rho$ (pcm/efpd)	-6.2	-4.2	-2.4	-2.8	-1.1	-1.4	-4.2	-6.0	-1.4
I_{acc}/P_{th} (mA/GW)	—	—	—	11.5	11.6	11.7	3.7	0	11.7
P_{acc}/P_{elec} (%)	—	—	—	7.2	7.2	7.2	2.3	0	7.3

Table 3 — Pu content, reactivity loss and accelerator requirements for double strata cores

Finally, table 4 shows global scenario parameters for a fixed size reactor fleet: 60 GWe installed power, producing 400 TWhe a year. These parameters are the fraction of the reactor fleet electricity produced by the second stratum burner reactors, that lies in the range 3-5%, the TRU inventory in reactors and cycle plants (i.e. for reprocessing and fuel fabrication), the annual amount of TRU wastes, when an elementary loss rate of 0.1% is assumed, and finally the reduction in TRU waste inventory or radiotoxicity, taken at 10000 years after storage, with respect to what is called the "open cycle", i.e. a reactor fleet of the same global power made only of (once-through) PWRs. The figures show that there is very little difference between scenarios involving critical or ADS TRU burners. This is not surprising, since the basic reactions (capture, fission) are the same in both cases.

Core type	Critical			"Twin" ADS			ADS		
Coolant	Na	Pb	He	Na	Pb	He	Na	Pb	He
Electricity prod. (%)	5.3	4.3	3.6	3.5	3.2	3.2	3.5	3.7	3.4
Inventory (t)									
Pu	492	492	473	499	498	478	471	466	474
Np	10.8	11.0	10.5	11.3	11.2	10.6	10.5	10.4	10.5
Am	44.8	43.6	26.2	44.1	43.5	26.2	24.7	22.6	24.5
Cm	14.5	14.1	10.8	14.9	14.7	11.6	10.9	9.7	11.5
Wastes (kg/y)									
Pu	37.9	37.7	36.5	38.2	38.1	36.8	35.9	35.5	36.5
Np	0.84	0.84	0.80	0.9	0.9	0.8	0.8	0.8	0.8
Am	3.50	3.40	2.25	3.5	3.5	2.4	2.0	1.8	2.2
Cm	1.19	1.15	1.10	1.2	1.2	1.1	0.9	0.8	1.1
Waste TRU mass red.	271	273	290	269	270	287	308	313	328
Radtox red. at 10^4 y	228	228	239	225	225	236	271	255	264

Table 4 — Scenario data for double strata cores

2.2. Double component scenarios.

These scenarios involve PWRs that send their TRU output into burners, plutonium being not recycled in separate units as it was in the double strata scenarios. Plutonium represents then roughly 90% of the feed to TRU burners: this means a fuel much more reactive (fissile), and then a further reduction in the fuel volume fraction (see table 5). The TRU burner are He-cooled reactors, either based on pin or particle fuel design. For pin design, there is no moderator present, while for the particle fuel design, the main subassembly support material is graphite. The fuel is made only of plutonium and minor actinides (no uranium).

Table 1 shows that the fuel volume fractions have to be decreased dramatically in order to keep an acceptable reactivity level. This means that an inert matrix would have to be used. Due to a smaller core volume and correlatively a higher specific power for the same fuel residence time, the burn-up is much greater for the particle fuel design.

Table 6 shows that in the pin fuel ADS core, with no moderator inside, the Doppler constant is quite low, while it is high for the particle fuel core due to the large amount of graphite present. To the contrary, the delayed neutron fraction is much lower in the particle fuel core, with the softest spectrum, due to the higher degradation of the plutonium isotopic composition, while it remains fairly high in the non moderated core that allows the lowest degradation of the Pu isotopic composition.

Core type	ADS	
Fuel design	pin	particle
Core power (MW_{th})	1500	1500
Fuel volume fract. (%)	7.6	8.8
Actinide load (kg)	6094	2828
Fuel resid. time (efpd)	900	900
Avg. power (W/cm^3)	176	407
Average BU (%)	21.3	43.4

Table 5 — General data for double component cores

Core type	ADS	
Fuel design	pin	particle
$\Delta\rho_{coolant}$ (pcm)	—	—
$K_{Doppler}$ (pcm)	-99	-845
β_{eff} (pcm)	238	70

Table 6 — Reactivity coefficients for double component cores

The plutonium content is much higher than for the double strata core, as shown in table 7, because of the very large content in the Pu+MA feed (roughly 90%). This means a higher reactivity loss (effect mitigated in the pin fuel design by the lower specific power), due to a lesser Pu (re)generation from captures on minor actinides, and thus higher beam intensities for a given core energy output than in double strata cores. ADS are clearly less attractive in this case, as 25 to 40% of the gross electrical output has to be used to feed the accelerator.

Core type	ADS	
Fuel design	pin	particle
Pu/(Pu+MA) (w%)	80.8	79.3
$\Delta\rho$ (pcm/efpd)	-8.56	-21.4
I_{acc}/P_{th} (mA/GW)	36.5	63.5
P_{acc}/P_{elec} (%)	22.8	39.7

Table 7 — Pu content, reactivity loss and accelerator requirements for double component cores

As now the burners have to fission all TRU nuclides coming from PWRs, the fraction of electricity produced by the TRU burners is much greater than it was for the MA burners in the double strata scenarios. The mass inventories are clearly dependent on the average burn-up achieved in the core: the greater the burn-up, the lower the inventory and the waste produced by reprocessing, as shown in table 8. For the double strata scenarios, this effect was somewhat masked by the inventory and waste stream due to the Pu burners in the first stratum, operating at fixed burn-up for all the scenarios.

Core type	ADS	
Fuel design	pin	Particle
Electricity prod. (%)	18.4	16.1
Inventory (t)		
Pu	387	206
Np	19.7	8.8
Am	44.6	17.8
Cm	11.5	18.8
Wastes (kg/y)		
Pu	36.4	18.9
Np	1.8	0.7
Am	4.3	1.6
Cm	1.1	1.7
Waste TRU mass red.	302	514
Radtox red. at 10^4 y	252	455

Table 8 — Scenario data for double component cores

2.3. Conclusion for closed cycle scenarios

The elementary loss rate at reprocessing being fixed, all scenarios show similar waste stream reductions with respect to the open cycle. For double strata scenarios, the individual variations are dampened by the first stratum waste output, specially the output from the Pu burners. For double component scenarios, the burn-up achieved impacts directly on the waste stream and inventory amounts.

The fraction of the reactor fleet electrical output due to MA burners ranges between 3 and 5% for the double strata scenarios, and between 16 and 18% for the double component scenarios.

Variations with the coolant used are insignificant, provided that enough subcriticality can be ensured (reactivity coefficients). The double strata MA burners exhibit better fuel reactivity regeneration properties than the double component Pu+MA burners, and so need smaller proton beam intensities for similar reactor powers.

The results quoted here are only prospective ones, because thorough fuel element design studies may change the geometry and composition of the fuel elements. Anyway, the fundamental trends are evidenced.

3. OPEN SCENARIOS : ONCE-THROUGH WITH HIGH BURN-UP

The objective here is to burn TRU as deeply as possible, avoiding further reprocessing. Deep TRU burning has two incentives : to burn fissile isotopes and to reduce TRU volume sent to the waste stream. In this respect, gas-cooled reactor technologies (e.g. GT-MHR [3]) seem to offer significant advantages in accomplishing the transmutation of plutonium isotopes and nearly total destruction of Pu-239 in particular. GT-MHR uses well thermalised neutron spectrum, operates at high temperature without the need for fertile material and employs ceramic-coated fuel. It utilises natural erbium as a non-fertile burnable poison with the capture cross section having a resonance at a neutron energy such that ensures a strong negative temperature coefficient of reactivity. The lack of interaction of neutrons with coolant (helium gas) means that temperature feedback is the only significant contributor to the power coefficient. As a matter of fact, no additional plutonium is produced since no U-238 is used.

A gas-cooled high temperature reactor or a separate irradiation zone in the center of GT-MHR assembly, coupled to an accelerator [4], could also provide an extremely fast neutron environment due to the same reason -- the helium coolant is essentially transparent to neutrons and does not change neutron energies. Since other actinides with an exception of plutonium are more inclined to fission in a fast neutron energy spectrum, one could consider an additional fast stage, following a thermal stage, in order to eliminate the remaining actinides.

Here we will describe the application of critical as well as sub-critical (accelerator-driven) GT-MHR for transmutation of TRUs originating from the spent nuclear fuel in the once-through cycle. Both thermal and fast stages are considered making a qualitative comparison of different concepts. The main goal is to obtain the maximum destruction of plutonium as well as to minimise the irradiated fuel radiotoxicity in the long term. MCNPX [5], MCNP4B [6], MONTEBURNS [7] and CINDER'90 [8] codes are employed at different stages of our simulations. The performances of the codes have been successfully benchmarked in Ref. [9] by simulating the fuel cycle of the high flux reactor at ILL Grenoble.

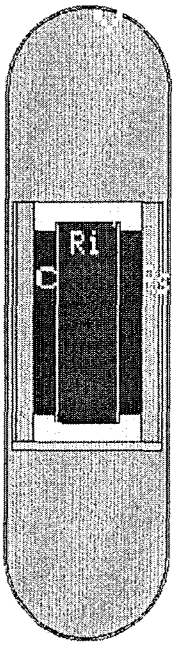
3.1. Modelling tools and procedure

The Gas Turbine - Modular Helium Reactor (GT-MHR) is an electric generation power plant (600MW$_{th}$) that couples a critical reactor with an efficient (~47%) energy conversion system [3]. Conceptual design of GT-MHR was developed in a joint project of Russia, USA, France and Japan with the major interest in Pu based fuel cycles [3].

A simplified 3D model of GT-MHR reactor which is shown in Fig. 1a has been created using MCNP4B geometry setup [6]. Further details on modelling can be found in [10], while some of the results have already been reported in [11]. MCNP4B was also used to obtain k-eigenvalues and neutron fluxes. For the subcritical Accelerator Driven GT-MHR (AD-GT-MHR), a single difference was the prevision for an accelerator target for neutron production located in the inner reflector. In this case the MCNPX code in proton source mode was applied to the calculations of neutron fluxes. MCNPX [5] was used to write a low energy ($E_n < 20$MeV) neutron source in the spallation target, that was employed for the burn-up calculations with MONTEBURNS [7]. Corresponding activities and radiotoxicities were calculated with CINDER'90 code system [8].

As soon as $k_{eff} < 1$ the length of the fuel cycle could be determined in the case of a critical system. For a sub-critical system, k_{eff} was "allowed" to vary within the interval where neutron multiplication could be still compensated by a proton accelerator, say, at maximum ~60MW of beam power of 1 GeV protons. When this condition was not fulfilled, the total core power was decreased with decreasing k_{eff}.

A typical neutron spectrum evolution for Pu fuel poisoned with natural Er is shown in Fig. 1b [11]. The observed increase of the thermal flux from 10% to 30% can be explained by the loss of Pu-239 and Pu-240 in addition to the lost of the burnable poison during the fuel burn-up. Indeed, the change of the energy spectra of neutrons will change the average cross sections to be used in the burn-up calculations, in some cases by a factor of two or more [10]. Therefore fuel evolution calculations have to be performed with corresponding variable neutron fluxes as it is done with MONTEBURNS [7]. We also found that typical averaged GT-MHR neutron fluxes in the active core may increase by 50-100 %, i.e. from ~1×10^{14} n/(cm^2 s) to ~2×10^{14} n/(cm^2 s) at the beginning and at the end of the fuel cycle respectively.



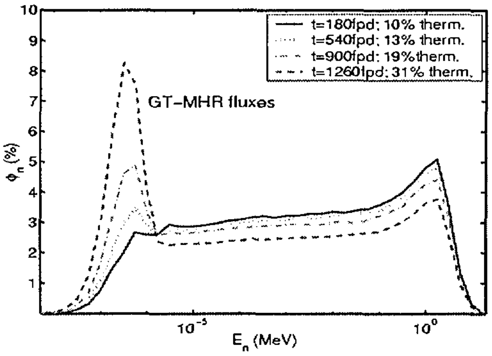


Figure 1a (on the left) — Lengthwise section view of GT-MHR reactor model. The following notation is employed: C – core(~8 m long), Rt - top reflector, Ri – inner reflector, Rb - bottom reflector, Rs - side reflector, and V - reactor vessel

Figure 1b(on the right) — Typical change of the averaged energy spectra of neutrons in the active core of GT-MHR for different fuel burn-up expressed in full power days (fpd).

3.2. Scenarios examined

In table 9 we fix the transuranic (TRU) waste composition to be transmuted. This table represents typical form of LWR discharge (40 GWd/ton burn-up) when uranium and fission products are separated. 1500 kg of the waste is taken arbitrarily.

Scenario S0. This is our reference point when TRU represented in table 9 is left to decay naturally, i.e. no irradiation takes place.

Nuclide	(%)	(kg)
237-Np	4.9	73.5
238-Pu	1.7	25.5
239-Pu	54.5	817.5
240-Pu	22.8	342.0
241-Pu	5.4	81.0
242-Pu	3.7	55.5
241-Am	5.7	85.5
243-Am	0.9	13.5
242-Cm	0.1	1.5
244-Cm	0.3	4.5
Total Pu	88.1	1321.5
Total TRU	100	1500

Table 9 — Initial composition and mass of the TRU considered in this study.

Scenario S1. In this case only Pu isotopes are placed in the critical GT-MHR for destruction. The length of the fuel cycle is ~1550 days. Total neutron fluence was ~1.7×10^{22} n/cm^2.
Scenario S2. This is a continuation of S1. Now GT-MHR is coupled to proton accelerator and runs in its sub-critical mode for another 300 days with decreasing k_{eff} ($k_{eff} \sim 0.90 \rightarrow 0.52$) and also decreasing reactor power P_{th} ($P_{th} = 1.0P_o \rightarrow 0.25P_o$). The accelerator power increases from ~33MW to ~66MW. Total neutron fluence (including S1) was ~2.2×10^{22} n/cm^2.
Scenario S3. In this case GT-MHR is coupled to the proton accelerator at the very beginning since full TRU composition is selected including isotopes of Np, Am and Cm. System starts with k_{eff} ~0.91 and runs for ~500 days with decreasing accelerator power until the core becomes critical. Now system runs in its critical mode (without accelerator) for another ~900 days. GT-MHR finishes its cycle as a sub-critical system after additional ~200 days of operation with final k_{eff} ~0.88. Total neutron fluence was ~2.2×10^{22} n/cm^2.
Scenario 4. This is a continuation of S3. GT-MHR continues running in its sub-critical mode for another 250 days with decreasing k_{eff} ($k_{eff} \sim 0.88 \rightarrow 0.60$) and consequently decreasing reactor power P_{th} ($P_{th} = 1.0P_o \rightarrow 0.30P_o$). The accelerator power should be increased from ~42MW to ~62MW. Total neutron fluence (including Scenario S3) was ~2.5×10^{22} n/cm^2.

3.3. Major results and discussion

Tables 10 and 11 contain the burn-up results obtained for 4 different scenarios considered. Scenario S1 shows that very high burn-up rates can be reached even if only a critical GT-MHR is considered: ~97% for Pu-239 and ~75% for all Pu isotopes. Indeed, coupling of the critical GT-MHR to an accelerator gives an extremely deep burn-up, 99.5% for Pu-239 and 84.4% for all Pu isotopes. These calculations confirm earlier estimates of the similar type reported in [4]. We note separately that after Scenario S1 there was no real decrease in the mass of Pu-241, simply because its destruction was compensated by its creation from Pu-240. Therefore, Scenario S2 is essential not only for deep burning of Pu-239, but also for considerable elimination of equally proliferation-offensive Pu-241.

Scenario S3 shows that mixing of waste plutonium with the rest of actinides (Np, Am, Cm) can influence considerably GT-MHR performances. Indeed, the system cannot start its cycle in the critical mode, i.e. an accelerator is needed already at the very beginning of the operation.

Scenario	Operation	Power	Duration (days)	Transmutation rate		
				Pu-239	Pu	TRU*
S1	critical	nominal	1550	97%	75%	61%
S1→S2	ADS	decreasing	+300	99.5%	84%	68%

Table 10 — Once-through burning in GT-MHR: loading of Pu isotopes only. Here TRU* includes not irradiated Np, Am and Cm (See table 9).

Scenario	Operation	Power	Duration (days)	Transmutation rate		
				Pu-239	Pu	TRU
S3	ADS+critical+ADS	nominal	1600	97%	71%	64%
S3→S4	ADS	decreasing	+250	98%	79%	72%

Table 11 — Once-through burning in GT-MHR : loading of full TRU vector.

Again like in the Scenario S2, Scenario S4 shows that in order to obtain deeper burn-up of fissile materials the system should be run as long as possible even with decreasing Although, Scenario S2 ends up with slightly better burnup rates both for Pu-239 and Pu-240, at the very beginning it requires full separation of Np, Am and Cm isotopes. In the case of Scenario S4, the mass of Pu-238 is actually increased due to the presence of Np-237 in the fuel, what is not the case for Scenario S2.

What about the waste radiotoxicity? Fig. 3 presents a change in radiotoxicity for Scenarios S0, S2 and S4 as.

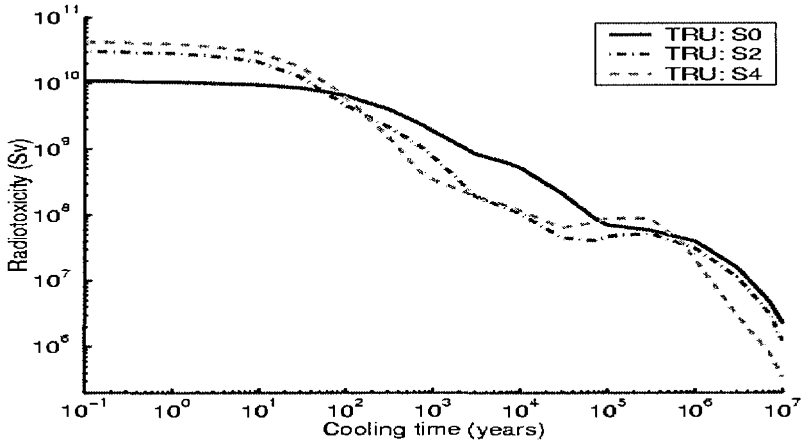


Figure 2 — A change in radiotoxicity of TRU for different scenarios considered: TRU:S0 - no irradiation, TRU:S2 - Scenario S2 and TRU:S4 - Scenario S4. Also see tables 9, 10 and 11..

described above. It is important to note that the curve TRU: S2 contains the contribution to the radiotoxicity due to ~180 kg of Np, Am and Cm isotopes not irradiated. As it is clearly seen from Fig. 3, the total radiotoxicity of the irradiated fuel is higher by a factor of 3-4 during first 100 years of cooling. Later curves cross and irradiated fuel becomes less radiotoxic only by a factor of 4-5 after 1000 years of cooling. After 100,000 years the radiotoxicity curves of irradiated fuel again approach the one corresponding to non irradiated TRU.

3.4. Conclusions for once-through cycles

The problem of elimination of Pu isotopes has been addressed in terms of once-through fuel cycle. We confirm that the GT-MHR technology offers the potential to eliminate essentially all weapons-useful material present in nuclear waste (~99.5% for Pu-239 and ~84.4% for all Pu isotopes). The use of accelerator is essential to provide the needed neutrons for deep burn-up of Pu-239 and an important further destruction of Pu-240 and Pu-241 in the thermal regime. In addition, wide spectrum of Pu isotopic compositions with or without isotopes of Np, Am and Cm prove GT-MHR potentials to use the Pu as fuel without generating large amounts of minor actinides. Most importantly, these deep burn-up levels are achieved with no intermediate plutonium reprocessing. After the plutonium and any fissile material was burned, further reprocessing if desired may be more acceptable. We note separately that none of the scenarios considered could reduce significantly the total waste radiotoxicity in the long term.

3.6. Closing up of once-through cycles

In this context we considered an additional fast stage, in order to eliminate the remaining actinides and further reduce the waste radiotoxicity at the same time. For this purpose we placed already irradiated fuel (discharge S2 given in the table 10 with Np, Am and Cm not irradiated as from table 9) around the spallation target. In other words, a separate fast zone was created in the center of the GT-MHR inner reflector. In order to increase further a relative actinide destruction in terms of σ_f/σ_c ratio, we added B-10 as a burnable poison (see table 12). In this way all thermal neutrons, rescattered to this fast zone from the inner reflector, were suppressed to reduce the regeneration of heavy elements. In this stage, we obtained additional burn-up of 15% during 3 years of irradiation. This preliminary result seems little attractive, nevertheless the value of transmuting even a relatively low volume of remaining actinides at the cost of reprocessing of already irradiated TRISO particles has to be studied in detail. Further investigations along these lines will be carried out in the future.

	GT-MHR Thermal region	GT-MHR Fast region (borated)
Np-237	0.006	0.21
Pu-238	0.011	1.64
Pu-240	0.002	0.33
Pu-242	0.004	0.63
Am-241	0.008	0.13
Am-243	0.002	0.20
Cm-244	0.029	0.51

Table 12 — Fission to absorption probability ratios for quickly decaying α-emitters in GT-MHR thermal region compared to GT-MHR fast borated region.

4. CONCLUSION

The elementary loss rate at reprocessing being fixed (here 0.1%) all multiple recycling scenarios show similar waste stream reductions with respect to the open cycle (here a factor 300). For double strata scenarios, individual variations are dampened by the first stratum waste output, mainly from the Pu burners. For double component scenarios, the burn-up achieved impacts directly on the waste stream and inventory amounts. The fraction of the reactor fleet electrical output due to MA burners ranges between 3 and 5% for the double strata scenarios, and between 16 and 18% for the double component scenarios. Variations with the coolant used are insignificant, provided that enough subcriticality can be ensured (reactivity coefficients). The double strata MA burners exhibit better fuel reactivity regeneration properties than the double component Pu+MA burners, and so need smaller proton beam intensities for similar reactor powers. The results quoted here are only prospective ones, because thorough fuel element design studies may change the geometry and composition of the fuel elements.

The once-through scenarios show that it is possible to burn waste in a single run up to some 70% fission rate, and that an accelerator helps in reaching this goal by allowing function in subcritical conditions; it also helps to reach very high Pu reductions. Indeed, highly proliferative (fissile) nuclides, such as Pu-239 and Pu-241 are almost totally eliminated during the process (a 99.5% reduction for Pu-239, and a 84% reduction for all Pu isotopes). However, the radiotoxicity reductions achievable with respect to the open cycle are a factor 3-5 at best with this burn-up. Further investigations will focus on the possibility to burn even more deeply the irradiated fuel by placing it into a fast spectrum region of the core.

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