HTR-N

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Report on strategy study on LWR/HTR symbiosis

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INTRODUCTION

This document is the **Deliverable 3.3.1** of the project **"High-Temperature Reactor Nuclear Physics, Waste and Fuel Cycle Studies"** (**HTR-N1**) of the European Unioun Fifth Framework program [1]. It is a merger of the following two documents, which have been included as Appendix A and Appendix B, respectively:

A. "*Scenario studies within a nuclear park composed of PWRs and GTMHR-type HTRs using reactor-grade plutonium*", by P. Bourdot [2], 43 pages. The original document has also been inserted into the SINTER database as HTR-N1 support document no. **HTR-N1-04/03-S-3.3.1-1**;

B. "*Utilisation/disposition of reactor-grade plutonium in HTR's*", by P. Bonin, D. Greneche, F. Carre, F. Damian and J.Y. Doriath [3], 15 pages. The original document has also been inserted into the SINTER database as HTR-N1 external document no. **HTR-N1-03/06-X-3.3.1-1**.

SUMMARY & CONCLUSIONS

In Task 3.3 of Work Package 3 of the HTR-N1 project the general fuel cycle issue for high-temperature gas-cooled reactors (HTRs) has been addressed within the frame of HTR-N program in order to assess the main features of HTRs with regard to all possible fuel cycles. The preliminary studies have shown that HTRs are able to accommodate a wide variety of mixtures of fissile and fertile materials without any significant modification of the core design. This unique flexibility is due to an uncoupling between the parameters of cooling geometry and the parameters that characterize neutronic optimisation (moderation ratio or heavy nuclide concentration and distribution).

Among other advantageous features, an HTR core has a better neutron economy than a light water reactor (LWR) because there is much less parasitic capture in the moderator (capture cross section of graphite is 100 times less than the one of water), in internal structures, and in fission products (because of a harder spectrum).

Moreover, thanks to the high strength of the coated particles HTR fuels are able to reach very high burnups, far beyond the possibilities offered by other fuels (except the special case of molten salt reactors).

These features make HTRs potentially interesting for closing the nuclear fuel cycle and stabilizing the plutonium inventory.

A large number of fuel cycle studies are already available today on three main categories of fuel cycles involving HTRs :

1. high-enriched uranium cycle, based on thorium utilization as a fertile material and high-enriched uranium as a fissile material
2. low-enriched uranium cycle (LEU), where only LEU is used (from 5 to 15 %)
3. plutonium cycle based on the utilization of plutonium only as a fissile material, with (or without) fertile materials.

Plutonium consumption at high burnups in HTRs has already been tested with encouraging results under the DRAGON project and at Peach Bottom. In the frame of HTR-N core studies have been performed on plutonium HTR cores in order to maximize plutonium consumption either for weapon-grade plutonium or for reactor grade plutonium (produced by PWRs). Limits in burnup due to core neutronics have been investigated for this type of core.

With these limits in mind, we have studied in some detail the Pu cycle in the special case of a reactor fleet made of a mixtures of LWRs and HTRs. It is reasonable to assume that if HTRs are to be deployed on an industrial scale, the will coexist during a long period of time with already existing LWRs. Thus we have investigated the symbiotic behaviour of LWRs producing plutonium and of HTRs burning it. Main conclusions from the studies summarised here below.

Core studies with a wide range of plutonium isotopic compositions suggest that HTRs might be able to use the plutonium as fuel with no major hurdle from the safety standpoint. For each plutonium compositions, limits on the possible applications of long fuel cycle lengths have been assessed. Long cycles and high burnups are possible if fluences of ~12 n/kb (a factor of 2 more than the common requirements) are technologically feasible.

Nevertheless, more detailed core neutronic analysis and thermal calculations are necessary to assess the reactivity control aspects, to define the appropriate fuel management, and to answer the issues related to power distribution, which are especially important in the case of the plutonium use.
The present study confirms that a symbiotic reactor fleet involving LWRs and Pu-burning HTRs might be a very effective way to stabilize the plutonium inventory while providing energy in safe and (hopefully) economical conditions.

To give an idea, an "all plutonium" HTR can burn about 100 kg of reactor grade plutonium per TWhe, instead of only 65 kg in a PWR using standard MOX fuel, that is an increase of 50 % in plutonium consumption. With such performances, plutonium inventories could be stabilized in a fleet of reactors composed of about 20 % of HTRs and 80 % of LWRs (percentage in terms of power generation).

To sum up, the results obtained in these studies show that HTRs could be very efficient plutonium burners. However, it must be stressed than even though a rather large experience has already been gained in HTR fuels, significant R & D effort would still be necessary to perfect and qualify a high-performance plutonium fuel on an industrial scale for this type of reactor.

REFERENCES

[1] "*High-Temperature Reactor Nuclear Physics, Waste and Fuel Cycle Studies (HTR-N1)*", Contract no. FIKI-CT-2001-00169, European Union Fifth Framework Program.

[2] P. Bourdot, "*Scenario studies within a nuclear park composed of PWRs and GTMHR-type HTRs using reactor-grade plutonium*", Technical Note/Note Technique NT-SPRC-LECy-2004-318, CEA, France.

[3] B. Bonin, D. Greneche, F. Carre, F. Damian & J.Y. Doriath, "*Utilisation/disposition of reactor-grade plutonum in HTRs*", Nuclear Technology 145, 266-274, March 2004; also presented as "Prospective studies of HTR fuel cycles involving plutonium", Proc. HTR 2002, Petten, the Netherlands.

APPENDIX A

Original document

P. Bourdot, "*Scenario studies within a nuclear park composed of PWRs and GTMHR-type HTRs using reactor-grade plutonium*", Technical Note/Note Technique NT-SPRC-LECy-2004-318, CEA, France; 45 pages.

The original document has also been inserted into the SINTER database as HTR-N1 support document no. **HTR-N1-04/03-S-3.3.1-1**.

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Note Technique

TITRE : SCENARIO STUDIES WITHIN A NUCLEAR PARK COMPOSED OF PWRs AND GTMHR-TYPE HTRs USING REACTOR-GRADE PLUTONIUM

AUTEUR(S) : P.BOURDOT

RÉSUMÉ : This Technote presents the results of scenario studies concerning a nuclear park composed of pressurised water reactors (PWRs) and gas turbine modular helium reactor type high temperature reactors (GTMHR-type HTRs) using reactor-grade plutonium. HTRs are integrated into the nuclear park from 2025. MOX fuel ratios in 2025 are identical to those in the mono-recycling scenario, producing 12% of the total energy generated by the nuclear plant park.

Priority is given to reprocessing UOX and MOX fuels. It is also necessary to recycle HTR fuel in order to follow through with scenarios projected beyond 2070.

In the first scenario, HTRs are introduced at a rate of 2 GWe per year, while MOX fuel in EPRs is phased out at the same time. At the equilibrium state in 2031, 20% of the nuclear park's electrical energy is generated by HTRs and 80% by UOX PWRs.
Beyond 2077, the proportion of PWRs composing the nuclear park is insufficient to be able to maintain a satisfactory Pu quality needed to fuel HTRs.

In the second scenario, the proportion of PWRs and HTRs has been modified to retain a Pu quality above 50% at the equilibrium. 17% of the nuclear park's electrical energy is produced by HTRs and 83% by UOX PWRs. The Pu quality makes it possible to follow through with this scenario as far as 2100.

In the first scenario (HTR Pu 20%), the Pu inventory in the fuel cycle decreases until it reaches 307t in 2070. The americium inventory present in irradiated fuel stocks and separated nuclear material represents 178t while the curium inventory is equivalent to 13t.

In the second scenario, the Pu inventory in the cycle is stabilised at 370t, with 17% of the nuclear park's electrical energy generated by HTRs. The americium inventory in irradiated fuel stocks and separated nuclear material is identical to that in the first scenario (178t). The curium inventory – related to the number of HTRs – is equivalent to 11t.

A comparison with other scenarios is discussed in chapter 8.

MOTS CLÉS : NEUTRONICS, FUEL CYCLE, SIMULATION, COSI, HTR, GTMHR

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SOMMAIRE

1. INTRODUCTION

This Technote discusses scenario study results concerning a nuclear park composed of PWRs and HTRs using reactor-grade plutonium. This study was carried out in the context of the C09 Common Interest Programme* with COGEMA.

2. TERMINOLOGY

PIC	:	Programme d'Intérêt Commun (*Common Interest Programme*)
GTMHR	:	Gas Turbine Modular Helium Reactor
SWU	:	Separative Work Unit
UOX	:	Uranium Oxide
MOX	:	Mixed Oxide
CORAIL	:	Fuel composed of a mixture of UOX and MOX fuel rods within the same sub-assembly
APA	:	Advanced Plutonium Assembly
EPR	:	European Pressurised Water Reactor
HTR	:	High Temperature Reactor

3. OBJECTIVES

This study is designed to investigate nuclear park scenarios composed of PWRs using 100% UOX and HTRs using reactor-grade plutonium. The study is programmed to end in 2070, as is the case for the CORAIL (cf. ref. 1), APA (cf. ref. 2) and HTR-U (cf. ref. 6) scenario studies. This date corresponds to the approximate programmed shutdown of the first EPR.

4. HYPOTHESES

Hypotheses retained for this study are:

4.1 Scenarios

For such scenarios, it was decided to simulate the integration of HTRs into the French nuclear park.

The quantity of energy generated is both constant and equivalent to 400 TWhe per year from 2000.

As far as 2010: hypotheses remain identical to those used in the open cycle scenario, mono-recycling, and the CORAIL (cf. ref. 1), APA (cf. ref. 2) and HTR-U (cf. ref. 6) scenario studies. In 2010, burn-up rates for UOX and MOX fuels are respectively 60 GWd/t and 55 GWd/t (cf. chapter 11, fig. 1&2).

From 2010 to 2025: mono-recycling of plutonium in the form of MOX in PWRs is continued at an identical pace. The proportion of energy generated by MOX in the nuclear park is equivalent to 12%. From 2015, EPRs gradually begin replacing the current reactors.

Beyond 2025, the two scenarios will differ only by their proportion of HTRs in operation.

	Rate of introducing HTRs (from 2025 to 2031)	Proportion of HTRs in the nuclear park
Scenario 1: HTR Pu (20%)	2 GWe/yr	20% (80 TWhe)
Scenario 2: HTR Pu (17%)	1.7 GWe/yr	17% (68 TWhe)

* *Programme d'Intérêt Commun (PIC)*

4.2 HTR Concept

The GTMHR concept belonging to GENERAL ATOMICS was chosen for these scenario studies and is discussed in Ref. 3.
The retained HTR concept:

600 MWth GTMHR, 284 MWe, Pu cycle
Irradiation time in the reactor has been set at 280 effective full power days (EFPD) regardless of the loaded plutonium vector.
HTR management = yearly management strategy based on a one third core unloading, with the average unloading burn-up being a function of the quality of loaded Pu.

4.3 Burn-up rates

Increasing burn-ups to 60 GWd/t for UOX fuel and 55 GWd/t for MOX fuel is carried out gradually. These burn-ups are reached in 2010 for UOX and 2006 for MOX (cf. chapter 11, fig. 1&2).

4.4 Fuel enrichment

The enrichment of natural uranium is carried out by gaseous diffusion with a release rate of 0.25% (U-235 content in depleted uranium).

4.5 Fuel fabrication

No specific constraints apply as far as UOX fuel fabrication plants are concerned.
The life-span of MOX and HTR fuel fabrication plants has been set at 2 years.

4.6 Fuel reprocessing

Fuel reprocessing losses have been estimated at 0.1% for U and Pu. In priority, the oldest batches of nuclear material are reprocessed before the more recent ones.
For scenario purposes, MOX and HTR fuels are assumed to be processable.
Plant capacities are adapted in relation to Pu requirements.

Fuel reprocessing priorities are:

- Up until 2025: UOX reprocessing only,
- 2025 to 2070: UOX and MOX reprocessing, and UOX and HTR fuel reprocessing when all MOX stocks have been reprocessed.

5. COMPUTER CODES AND MODELS

Version 5.1.4 of the COSI scenario computer code was chosen for these studies.
The CESAR evolution computer code adapted to the 4.32 COSI code was also chosen.
The CESAR database – needed for core evolution calculations – was based on a "simplified" scheme of neutronic calculations for different Pu qualities. In this "simplified" scheme, the evolution of Pu concentrations is based on the calculation of the fuel element geometry in an infinite environment (calculation in the APOLLO2 computer code). The unloading burn-up rate – used to assess unloading materials – is based on the calculation of core neutron leakage, which helps determine the $k_{effective}$ of the reactor core at the end of cycle.

CESAR database No.	fissile Pu %	Pu mass/ reload (t)	Burn-up (MWd/t)
874	64.2	293	575
875	56.3	357	490
876	52.5	397	425
877	51.2	450	385
878	50.3	497	340

6. OPTIMISATION OF SCENARIOS

The reprocessing of the nuclear park's fuel stocks was chosen as the optimisation parameter.
Optimisation of fuel reprocessing was applied in scenario 1 (HTR Pu 20%).

Two reprocessing methods were studied between 2025 and 2070:

- UOX, MOX or HTR fuel:

  - The launching of HTRs fuelled with Pu from UOX in 2025. A Pu quality (fissile Pu/ total Pu) of 62% and an annual Pu reloading at equilibrium of 12t (excluding graphite) are used.

  - The quantity of UOX fuel available for reprocessing is no longer sufficient from 2038, which implies reprocessing UOX and MOX fuel. The Pu quality at loading drops to 55% in 2068 (annual Pu reloading at equilibrium of 15t, excluding graphite).

  - MOX stocks have run out in 2068. It is also necessary to reprocess HTR fuel. The Pu quality in HTRs at reloading (45%) becomes inadequate. Analysis of the use of plutonium in HTRs (plutonium from PWRs [4] and plutonium multi-recycling in HTRs [5]) revealed a threshold level for the content of fissile plutonium at loading (50%) below which the margin of core reactivity at start-up is no longer sufficient, thereby shortening the fuel cycle length. This threshold is related to the physical characteristics of HTRs. Therefore, the high proportion of neutrons in the epithermal range combined with a degraded plutonium vector – high proportion of Pu^{240} and Pu^{242} – greatly limits the mass of fuel that can be loaded, which affects the fuel cycle length.

- UOX-MOX or UOX-HTR mixture:
  In this scenario, the quantity of UOX fuel has been reduced in order to launch the HTR park. This saving in good-quality Pu makes it possible to continue the scenario beyond 2070.

  - The launching of the HTR park in 2025 using Pu from a UOX-MOX mixture with respective proportions of 70% and 30% at reprocessing. A Pu quality of approximately 57% (fissile Pu/ total Pu) is obtained, which corresponds to an annual reloading at equilibrium of 15t.

- MOX fuel has run out in 2047. HTRs are fuelled with Pu from a UOX-HTR mixture with respective proportions of 98.75% and 1.25% (excluding graphite) at reprocessing. A Pu quality of about 52.5% (fissile Pu/ total Pu) is obtained, which corresponds to an annual reloading at equilibrium of 16.7t.

- UOX stocks required to meet the above-mentioned proportions are no longer sufficient in 2077, as the Pu quality falls to 45% (cf. chapter 12 - fig. 3).

The second method of reprocessing retained for both scenarios discussed in this Technote is:

- 100% UOX until 2025,
- A UOX-MOX mixture at the time HTRs are launched with 70% UOX at reprocessing,
- A UOX-HTR mixture when MOX stocks have run out, with 98.75% UOX at reprocessing.

7. SCENARIO STUDY RESULTS

7.1 Scenario 1 (HTR Pu 20%)

- Percentage of energy at equilibrium: 80% UOX and 20% HTR Pu,
- Fuel reprocessing:
  - 100% UOX until 2025;
  - UOX-MOX mixture from 2025 to 2046, with 70% UOX at reprocessing,
  - UOX-HTR mixture from 2047 to 2076, with 98.75% UOX at reprocessing.

Results are illustrated in annex 2 (cf. chapter 12). Mass quantities are expressed in tonnes of heavy metal.

The following aspects were remarked:

The proportion of PWRs is too low to maintain a satisfactory quality of Pu required to reload HTRs beyond 2077.

The Pu inventory in 2070 represents 307.3 tonnes and is distributed within the nuclear park as such: 210.5 tonnes in fuel stocks, 62.9 tonnes in reactors and 33.9 tonnes in reprocessing plants (cf. chapter 12, fig. 4). The Pu quality is equivalent to 45.3% (fissile Pu/ total Pu). The Pu inventory does not consider Pu^{240} from curium present in stocks of separated minor actinides.

Concerning the quality and content of Pu in new standard MOX assemblies, the Pu content reaches 9.6% in 2030, whereas the Pu quality falls from 67.1% in 2010 to 61.9% in 2030.
The Pu quality in HTR assemblies at loading falls from 57.2% in 2025 to 52.7% in 2070 (cf. chapter 12, fig. 3).

The quantity of reprocessed fuel in 2070 is equivalent to 962.4 tonnes of UOX and 12.2 tonnes of HTR fuel (excluding graphite). Beyond this date, the quantity of UOX fuel available for reprocessing rapidly falls to 656 tonnes in 2075, which no longer makes it possible to maintain a Pu quality needed to fuel HTRs (cf. chapter 12, fig. 5&6).

Fuel fabrication requirements are listed in chapter 12, fig. 7.

In terms of radioactive waste storage requirements, 4,134 tonnes of UOX and 356 tonnes of HTR fuel need to be stored in 2070. MOX fuel has been completely reprocessed (cf. chapter 12, fig. 8).

The total mass of minor actinides in irradiated fuel and separated MA stocks represents approximately 250 t in 2070, including 178 t of Am and 13 t of Cm (cf. chapter 12, fig. 10).

Annual requirements in natural uranium have been estimated at 6,690 tonnes in 2070 (cf. chapter 12, fig. 11).

Annual requirements in separative work units (SWU) have been estimated at 5.1M SWU in 2070 (cf. chapter 12, fig. 12).

An annual flux of reprocessed uranium has been estimated at 820 tonnes and an inventory of 64,800 tonnes in 2070 (cf. chapter 12, fig. 13).

The depleted uranium inventory in 2070 has been estimated at 579,000 tonnes (cf. chapter 12, fig. 14).

7.2 Scenario 2 (HTR Pu 17%)

- Percentage of energy at equilibrium: 83% UOX and 17% HTR Pu,
- Fuel reprocessing:
  - 100% UOX until 2025;
  - UOX-MOX mixture from 2025 to 2049, with 70% UOX at reprocessing,
  - UOX-HTR mixture beyond 2050, with 98.75% UOX at reprocessing.

Results are illustrated in annex 3 (cf. chapter 13). Mass quantities are expressed in tonnes of heavy metal.

The following aspects were remarked:

The proportion of PWRs is sufficient enough to maintain a satisfactory Pu quality required to fuel HTRs until 2100 – programmed end of the scenario studies.

The Pu inventory in 2070 represents 370.1 tonnes and is distributed within the nuclear park as such: 273.3 tonnes in fuel stocks, 64.2 tonnes in reactors and 32.6 tonnes in reprocessing plants (cf. chapter 13, fig. 4). The Pu quality is equivalent to 49.5% (fissile Pu/ total Pu). The Pu inventory does not consider Pu^{240} from curium present in stocks of separated minor actinides.

Concerning the quality and content of Pu in new standard MOX assemblies, the Pu content reaches 9.6% in 2030, whereas the Pu quality falls from 67.1% in 2010 to 61.9% in 2030.
The Pu quality in HTR assemblies falls from 57.1% in 2025 to 51.7% in 2070 (cf. chapter 13, fig. 3).

The quantity of reprocessed fuel in 2070 is equivalent to 919.5 tonnes of UOX and 11.6 tonnes of HTR fuel (excluding graphite). The quantity of UOX fuel available for reprocessing makes it possible to maintain a Pu quality needed to fuel HTRs until the end of the study in 2100 (cf. chapter 13, fig. 5&6).

Fuel fabrication requirements are listed in chapter 13, fig. 7.

In terms of radioactive waste storage requirements, 9,279 tonnes of UOX and 332 tonnes of HTR fuel need to be stored in 2070. MOX fuel has been completely reprocessed (cf. chapter 13, fig. 8).

The total mass minor actinides in irradiated fuel and separated MA stocks represents approximately 250 t in 2070, including 178 t of Am and 13 t of Cm (cf. chapter 13, fig. 10).
The quantity of curium is lower than that in scenario 1 as curium mainly comes from HTRs.

Annual requirements in natural uranium have been estimated at 6,940 tonnes in 2070 (cf. chapter 13, fig. 11).

Annual requirements in separative work units (SWU) have been estimated at 5.3M SWU in 2070 (cf. chapter 13, fig. 12).

An annual flux of reprocessed uranium has been estimated at 850 tonnes and an inventory of 60,900 tonnes in 2070 (cf. chapter 13, fig. 13).

The depleted uranium inventory in 2070 has been estimated at 589,000 tonnes (cf. chapter 13, fig. 14).

The situation in 2070 is described in the following tables:

HTR-Pu 20%: The situation in 2070

Nuclear park Pu stocks

	Stocks	Reprocessing plants	Reactors	Total
Pu only	210.5 t	33.9 t	62.9 t	307.3 t

Average Pu isotopes present in the nuclear park

Pu 238	Pu 239	Pu 240	Pu 241	Pu 242	fissile Pu / total Pu
7.7 %	28.6 %	22.6 %	16.6 %	24.4 %	45.3 %

Minor actinides in irradiated fuel and separated nuclear materials

Am	Cm	Total Am + Cm (t)	Np (tonnes)
177.6 t	13.1 t	190.7 t	58.6 t

Average Pu quality, content and mass loaded in HTRs

fissile Pu / total Pu	Mass (excluding graphite)
52,7 %	16.7 t

Annual fuel fabrication requirements

SWU	Natural U	UOX (mass of fuel rods)	MOX (mass of fuel rods)	HTR
$5.13\ 10^{6}$	6688 t	656 t	0 t	16.7

Annual fuel reprocessing requirements

Mass of reprocessed UOX	Mass of reprocessed MOX	Mass of reprocessed HTR	Pu extracted
962.4 t	0 t	12.2 t	16.7 t

Inventory of stocks

Irradiated fuel				depleted U	reprocessed U
UOX	MOX	HTR	Total		
4,134 t	0 t	356 t	4,490 t	579,000 t	64,800 t

HTR-Pu 17%: The situation in 2070

Nuclear park Pu stocks Inventaire Pu				
	Stocks	Reprocessing plants	Reactors	Total
Pu only	277273.3 t	32.6 t	64.2 t	370.1 t

Average Pu isotopes present in the nuclear park					
Pu 238	Pu 239	Pu 240	Pu 241	Pu 242	fissile Pu / total Pu
6.5 %	34 %	23.8 %	15.5 %	20.3 %	49.5 %

Minor actinides in irradiated fuel and separated nuclear materials			
Am	Cm	Total Am + Cm (t)	Np (tonnes)
177.5 t	11.3 t	188.8 t	59.5 t

Average Pu quality, content and mass loaded in HTRs	
fissile Pu / total Pu	Mass (excluding graphite)
51.4 %	16.1 t

Annual fuel fabrication requirements				
SWU	natural U	UOX (mass of fuel rods)	MOX mass of fuel rods)	HTR
$5.32\ 10^6$	6939 t	680.6 t	0 t	15.9

Annual fuel reprocessing requirements			
Mass of reprocessed UOX	Mass of reprocessed MOX	Mass of reprocessed HTR fuel	Pu extracted
919.5 t	0 t	11.6 t	16.1 t

Inventory of stocks					
Irradiated fuel				Depleted U	Reprocessed U
UOX	MOX	HTR	Total		
9,279 t	0 t	332 t	9,611 t	589,000 t	60,900 t

8. COMPARAISON WITH OTHER SCENARIOS

Comparison of Pu-fuelled HTR scenario with the other PIC scenarios (ref. <1> <2> and <6>). This comparison is carried out in 2070.

	Open Cycle	Mono-recycling	HTR-U	CORAIL	APA	HTR (20%)	HTR (17%)
Pu inventory in fuel cycle	820 t	599 t	568 t	364 t	288 t	307.3 t	370.1 t
Pu stocks	786 t	497 t	448 t	161 t	156 t	210.5 t	273.3 t
Pu waste	< 0,2 t	< 1 t	< 1 t	< 1 t	< 1 t	1 t	1 t
Pu content before fuel loading	-	9.9 %	11.9%	11.6 %	12.0 % constant (hypothesis)	52.7 %	51.4 %
Average Pu quality fissile Pu/ total Pu (excluding Am1)	59,4 %	52.9 %	53.6 %	47.7 %	41.1 %	45.3 %	49.5 %
Minor actinide inventory (irradiated fuel and separated material)	Am = 135 t Np = 64 t Cm = 4 t	Am = 151 t Np = 61 t Cm = 9 t	Am = 152 t Np = 59 t Cm = 9 t	Am = 150 t Np = 58 t Cm = 15 t	Am = 139 t Np = 57 t Cm = 14 t	Am = 177.6 t Np = 58.6 t Cm = 13.1 t	Am = 177.5 t Np = 59.5 t Cm = 11.3 t
Annual fuel reprocessing requirements	0 t	790 t (100% UOX)	672 t (83% UOX 17% MOX)	922 t (79% CORAIL, 21% UOX)	910 t (87% UOX, 13% APA)	962.4 t (98.75% UOX 1.25% HTR excl. graphite)	919.5 t (98.75% UOX 1.25% HTR excl. graphite)
Annual Pu requirements	0 t	9.8 t	12.9 t	25.2 t	16.4 t	16.7 t	16.1 t
Annual MOX fuel fabrication requirements	0 t	99.5 t (60 GWd/t)	108.5 t (55 GWd/t)	218 t	0 t	0 t	0 t
Annual UOX fuel fabrication requirements	820 t	720.5 t	556.5 t	659 t	695 t	656 t	680.6 t
Waste storage requirements	59,800 t UOX 2,115 t MOX	5,220 t UOX 7,520 t MOX	2,782 t UOX 5,507 t MOX 2,068 t HTR	4,550 t UOX 957 t CORAIL	5,790 t UOX 1,660 t APA	4134 t UOX 0 t MOX 356 t HTR	9279 t UOX 0 t MOX 332 t HTR
Annual nat. U needs	8,360 t	7,350 t	7,417 t	6,720 t	6,760 t	6,688 t	6,939 t
Annual SWU needs	6.41	5.63	6.00	5.15	5.14	5.13	5.32
Reprocessed U inventory	14,600 t	62,900 t	61,500 t	71,500 t	63,000 t	64,800 t	60,900 t
Depleted U inventory	678,000 t	602,000 t	609,000 t	558,000 t	689,000 t	579,000 t	589,000 t

Comparison in 2070

Data for the MULTIMOX THTC scenario is not provided as this scenario is not viable beyond 2025 owing to the fact that the Pu content threshold limit of 12% in MOX fuel is exceeded.

Two scenario types are illustrated in the table in the previous paragraph:

- Open cycle and mono-recycling scenarios on the left-hand side of the table,
- Multirecycling scenarios on the right-hand side of the table.

Several conclusions were drawn from this comparison:

In comparison to multirecycling scenarios, replacing UOX and MOX fuelled reactors with plutonium-fuelled GTMHR type HTRs produces the following situation in 2070:

Scenario 1: HTR Pu 20% of the nuclear park:
- Pu inventory diminished by 307 tonnes, yet this scenario is not viable beyond 2077.
- Inventory of minor actinides in irradiated fuel and separated materials equivalent to 250 tonnes. The annual Pu-HTR production of minor actinides is equivalent to 12.6 kg/TWhe with 65% americium and 5% curium.
- Annual needs in natural uranium and SWUs are identical to multirecycling scenario needs.

Scenario 2: HTR Pu 17% of the nuclear park:
- Pu inventory stabilised at 370 tonnes,
- Inventory of minor actinides in irradiated fuel and separated materials identical to scenario 1.
- Annual needs in natural uranium and SWUs are identical to multirecycling scenario needs.

9. CONCLUSION

This Technote provides the results of scenario studies focusing on a nuclear park composed of PWRs and GTMHR-type HTRs fuelled with plutonium. HTRs are integrated into the nuclear park from 2025. The reprocessing of HTR fuel is deemed necessary in these scenarios in order to continue operations beyond 2070.
In order to maintain a satisfactory Pu quality required to fuel HTRs beyond 2077, the proportion of PWRs at equilibrium in the nuclear park must represent at least 83% of the total electrical production.

The replacement of UOX and MOX fuelled reactors with GTMHR-type HTRs fuelled with plutonium – producing 20% of the total electrical production – generates a Pu inventory in the fuel cycle of 307 tonnes, including a stock of 210 tonnes. The americium inventory in irradiated fuel and separated materials represents 178 tonnes. The curium inventory represents 13 tonnes.
With regards to scenario 2, with 17% of the total electrical production generated by HTRs, the Pu inventory in the fuel cycle represents 370 tonnes, including a stock of 273 tonnes. The americium inventory in irradiated fuel and separated materials is identical to scenario 1 (178 t). The curium inventory – related to the number of operational HTRs – represents 11 tonnes.

A comparison with other scenarios is discussed in paragraph 8.

10. REFERENCES

<1> Scénario de recyclage du Pu dans le combustible CORAIL
SPRC/LECy-2002/317 indice 0

<2> Scénario de recyclage du Pu dans le combustible APA
SPRC/LECy-2003-300 indice 0

<3> Analyse des capacités des réacteurs à haute température (HTR) sous l'aspect de l'utilisation des matières fissiles
Rapport SERMA-R-5981.

<4> X. RAEPSAET, F. DAMIAN and M. LECOMTE, "Fuel cycle performances in High Temperature Reactor", International Conference on Future Nuclear System - Global'99

<5> F. DAMIAN, X. RAEPSAET and M. LECOMTE, "Mastery of the Plutonium in High Temperature Reactor", International Conference on Future Nuclear System - Global'01

<6> Etude de scénario dans un parc constitué de REP et de HTR type GTMHR fonctionnant à l'Uranium
SPRC/LECy-2003-315 indice 0

ANNEX 1 : PWR FUEL BURN-UPS

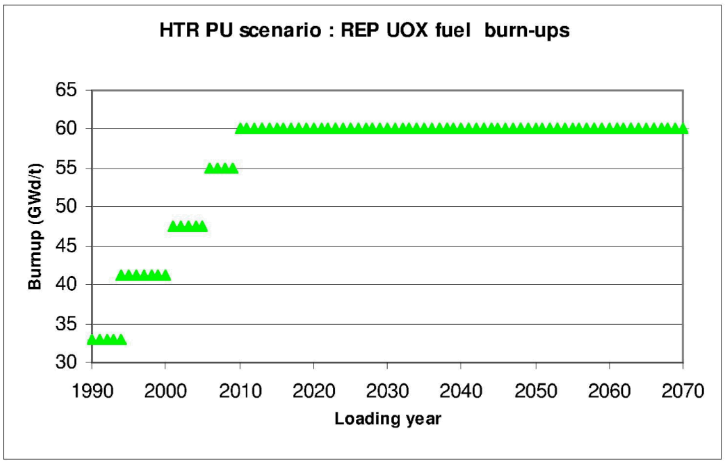

Figure 1

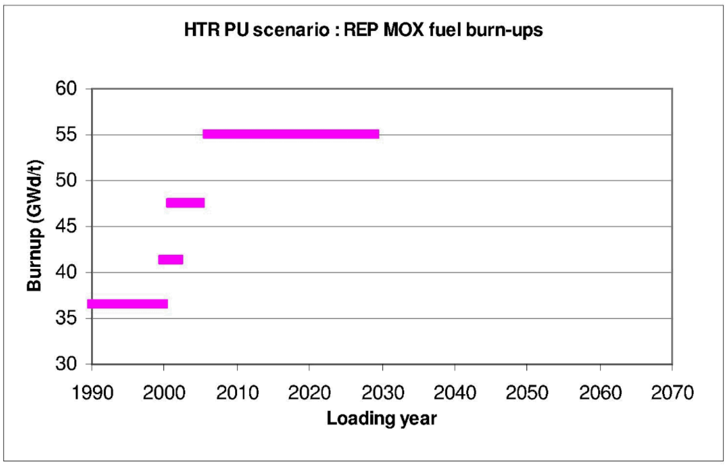

Figure 2

12. ANNEX 2 : HTR PU (20%)

HTR PU scenario (20%) – Energy production by fuel type (TWhe)

Year	UOX	MOX	HTR	Total
1990	291	9	0	300
1995	339	11	0	350
2000	364	36	0	400
2005	350	50	0	400
2010	351	49	0	400
2015	351	49	0	400
2020	351	49	0	400
2025	346	40	13	400
2030	320	0	80	400
2035	320	0	80	400
2040	320	0	80	400
2045	320	0	80	400
2050	320	0	80	400
2055	320	0	80	400
2060	320	0	80	400
2065	320	0	80	400
2070	320	0	80	400

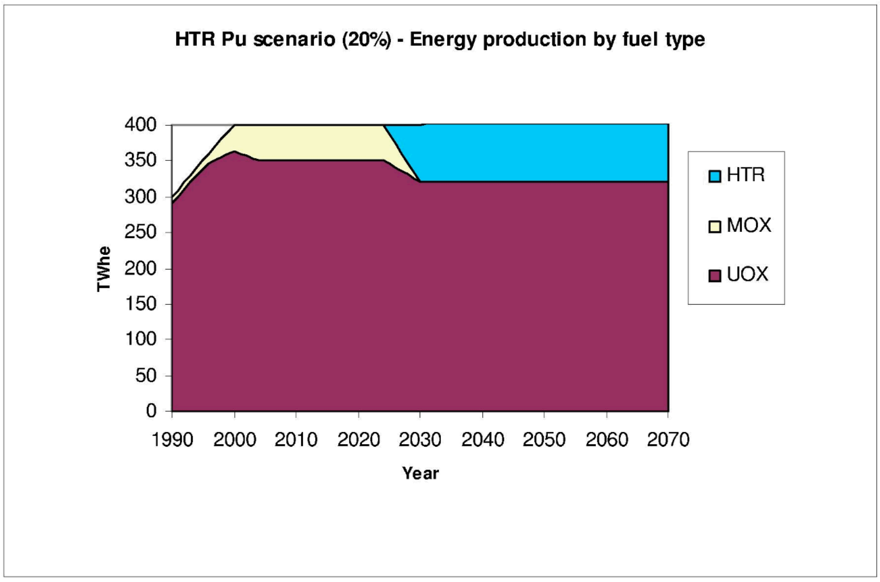

Figure 1

HTR PU scenario (20%) - Plutonium available in irradiated fuel stocks (t)

Year	HTR	UOX	MOX
2000	0.0	65.2	9.1
2005	0.0	69.7	25.0
2010	0.0	70.7	49.7
2015	0.0	68.7	79.2
2020	0.0	65.8	107.3
2025	0.1	61.0	114.9
2030	4.8	67.1	102.0
2035	23.5	84.2	80.4
2040	54.2	101.5	44.3
2045	76.9	105.8	11.3
2050	87.2	92.5	0.0
2055	96.3	71.2	0.0
2060	108.5	50.0	0.0
2065	120.9	29.2	0.0
2070	132.3	11.1	0.0
2075	141.6	1.6	0.0
2080	145.2	0.0	0.0
2085	145.3	0.0	0.0

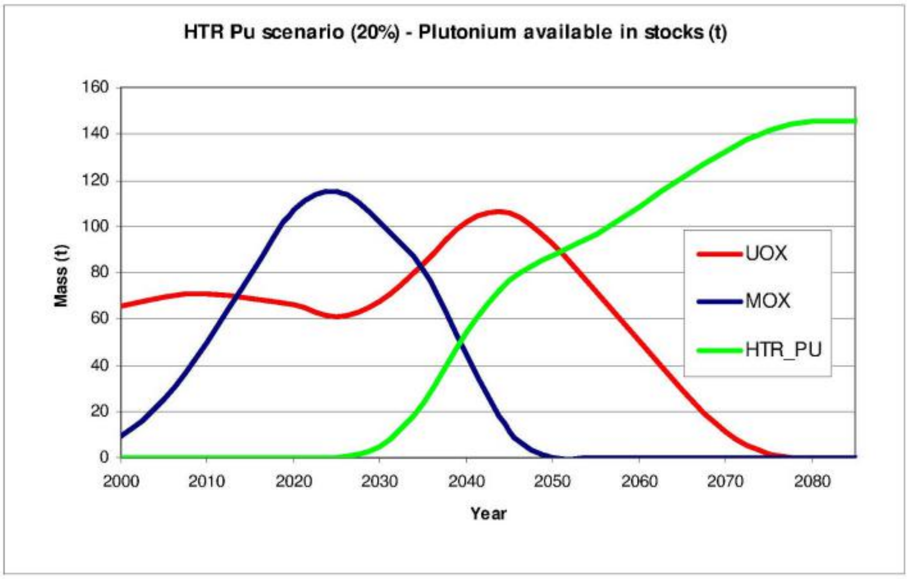

Figure 2

HTR PU scenario (20%) – Content and average Pu quality for fresh MOX assemblies

Year	Pu Content (%)	Pu quality (%)
2010	8.0	67.1
2020	8.9	64.3
2030	9.6	61.9

HTR PU scenario (20%) - Average Pu quality for fresh HTR-Pu assemblies

Year	Pu quality (%)
2 025	57.2
2 030	56.9
2 040	55.3
2 050	53.1
2 060	52.1
2 070	52.7
2 080	45.8

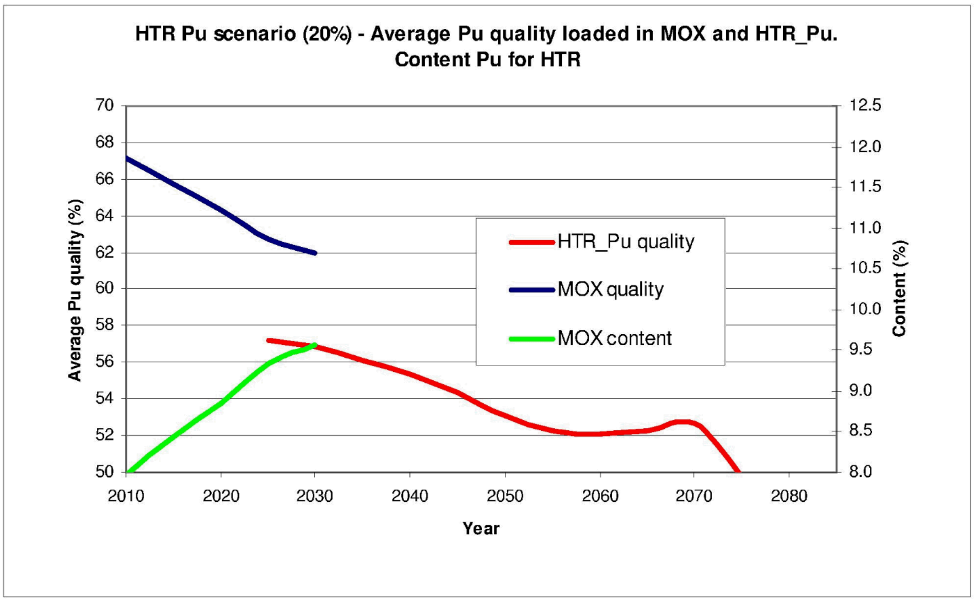

Figure 3

HTR PU scenario (20%) – Nuclear park Pu stocks (t)

Year	Plants	Reactors	Stocks	Total	Total (Pu+Am1)
2000	19.4	48.8	137.7	205.8	211.6
2005	16.8	66.8	162.1	245.8	254.1
2010	17.9	58.4	203.2	279.5	291.0
2015	18.8	75.2	216.3	310.3	325.1
2020	20.0	77.2	241.6	338.8	357.4
2025	33.1	84.6	248.4	366.1	386.3
2030	30.1	89.1	254.1	373.3	392.1
2035	30.1	59.9	275.1	365.2	384.7
2040	30.2	58.5	269.4	358.1	379.5
2045	33.6	58.5	258.6	350.6	374.3
2050	33.6	63.2	246.5	343.4	366.6
2055	33.7	63.0	237.7	334.3	357.4
2060	33.7	62.9	228.5	325.1	348.5
2065	33.8	62.9	219.3	316.1	340.3
2070	33.9	62.9	210.5	307.3	332.6

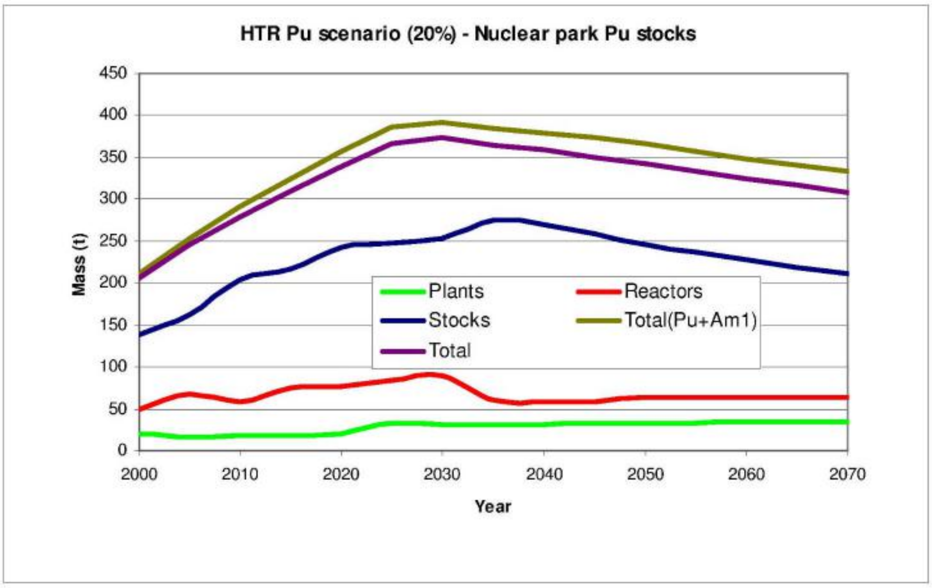

Figure 4

HTR PU scenario (20%) – Fuel reprocessing requirements (t)

Year	UOX	MOX	HTR (excluding graphite)
1990	290.4	0.0	0.0
1995	656.9	0.0	0.0
2000	956.3	0.0	0.0
2005	1032.9	0.0	0.0
2010	988.1	0.0	0.0
2015	901.4	0.0	0.0
2020	916.9	45.9	0.0
2025	765.1	139.5	0.0
2030	530.5	193.6	0.0
2035	420.1	180.1	0.0
2040	442.3	157.3	1.0
2045	699.0	78.3	6.6
2050	967.6	0.7	12.3
2055	987.3	0.0	12.5
2060	982.0	0.0	12.4
2065	970.3	0.0	12.3
2070	962.4	0.0	12.2

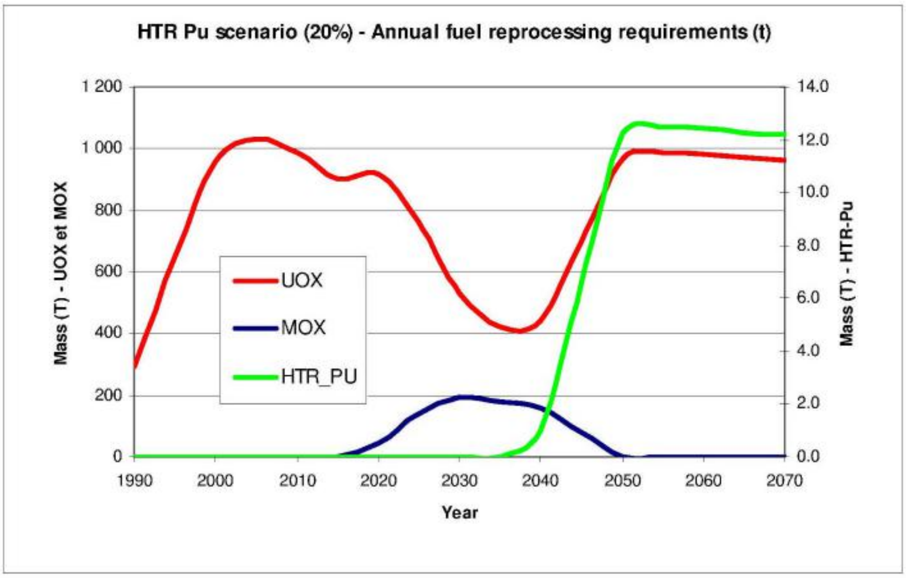

Figure 5

HTR PU scenario (20%) – Reprocessed Pu

Year	Reprocessed Pu for MOX (t)	Reprocessed Pu for HTR (t)	Total reprocessed Pu (t)
2 010	8.8	-	8.8
2 020	9.7	-	9.7
2 025	7.8	5.0	12.8
2 030	1.8	15.8	17.6
2 040	-	15.0	15.0
2 050	-	16.5	16.5
2 060	-	16.7	16.7
2 070	-	16.7	16.7

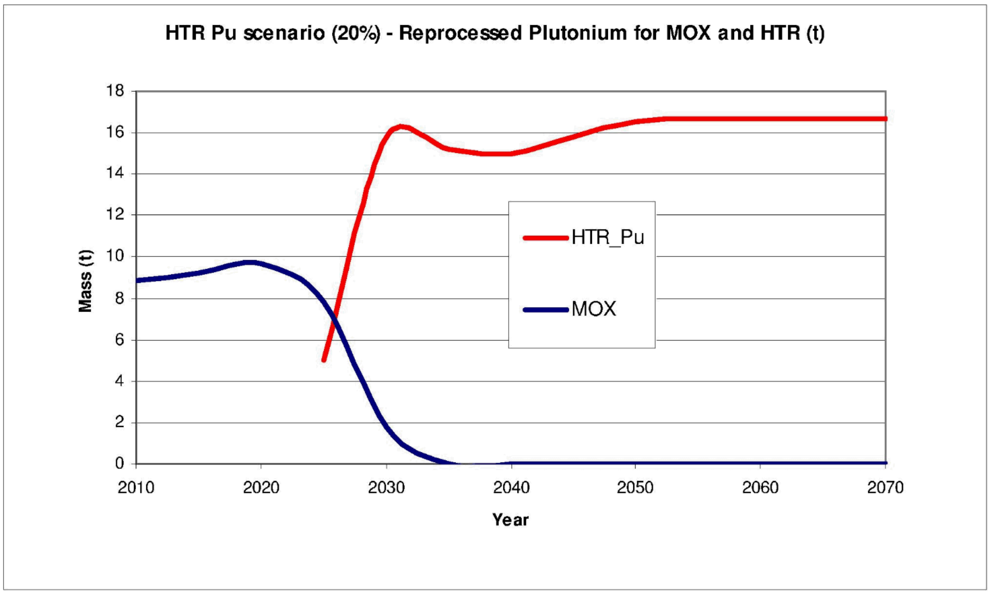

Figure 6

HTR PU scenario (20%) -– Annual fuel fabrication requirements (t)

Year	UOX	MOX	HTR
1990	865.2	30.3	0.0
1995	1171.5	77.1	0.0
2000	1032.3	118.7	0.0
2005	943.8	135.6	0.0
2010	828.0	120.0	0.0
2015	786.0	118.4	0.0
2020	717.6	106.9	0.0
2025	694.1	74.0	10.3
2030	665.8	24.7	14.3
2035	656.0	0.0	15.0
2040	656.0	0.0	15.2
2045	656.0	0.0	15.9
2050	656.0	0.0	16.7
2055	656.0	0.0	16.7
2060	656.0	0.0	16.7
2065	656.0	0.0	16.7
2070	656.0	0.0	16.7

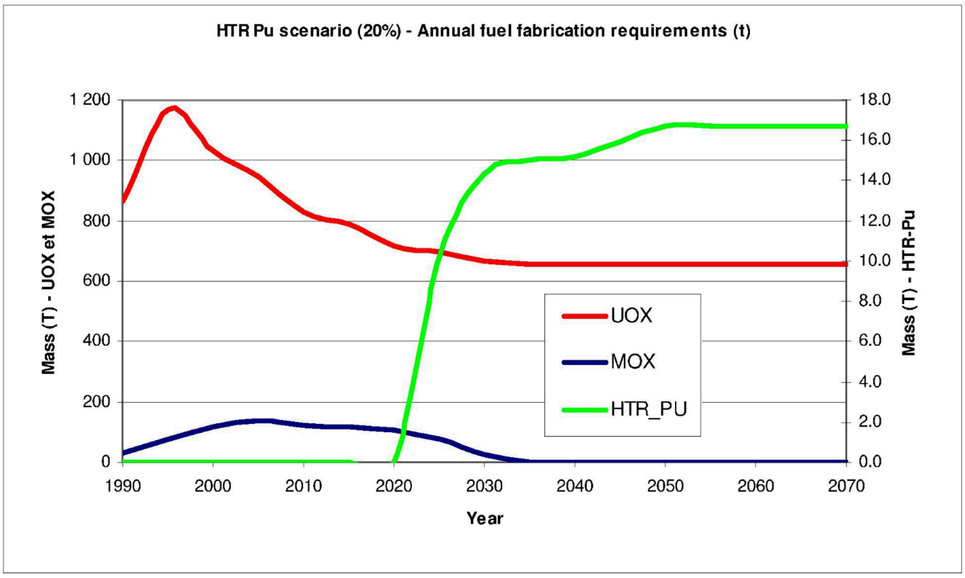

Figure 7

HTR PU (20%) scenario — Waste storage requirements for irradiated fuel (t)

Année	UOX	MOX	HTR
1990	9414	0	0
1995	10813	218	0
2000	11789	527	0
2005	11371	1007	0
2010	10609	1550	0
2015	9847	2115	0
2020	8945	2565	0
2025	8340	2591	15
2030	8734	2170	46
2035	9920	1510	113
2040	11145	711	187
2045	11451	162	241
2050	10424	0	270
2055	8782	0	291
2060	7141	0	312
2065	5539	0	334
2070	4134	0	356

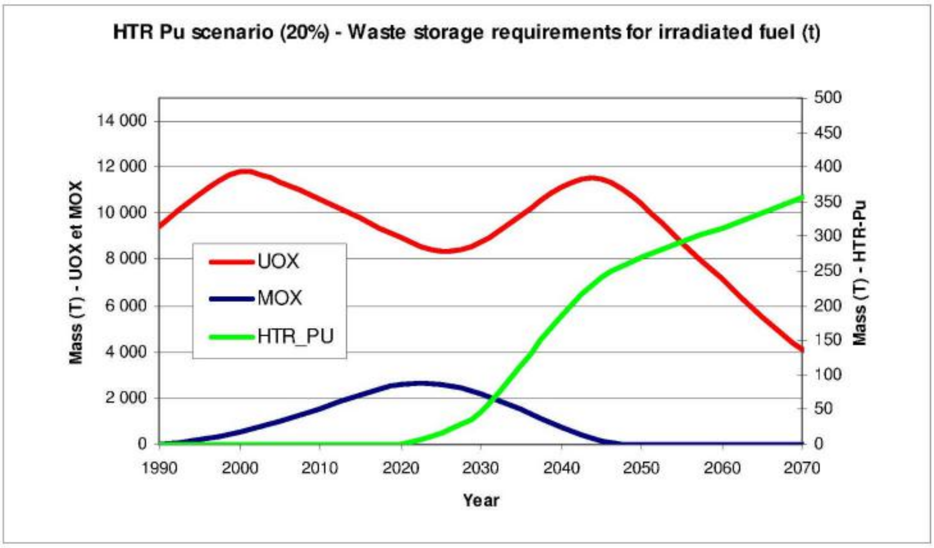

Figure 8

HTR PU scenario (20%) –– Minor actinides flux in reprocessing (t)

Year	Am	Np	Cm	Total
1990	0.15	0.13	0.01	0.29
1995	0.44	0.27	0.02	0.72
2000	0.70	0.39	0.02	1.11
2005	0.82	0.45	0.03	1.30
2010	0.88	0.49	0.04	1.41
2015	0.94	0.53	0.05	1.52
2020	1.41	0.65	0.08	2.15
2025	2.06	0.68	0.13	2.87
2030	2.32	0.56	0.16	3.04
2035	2.19	0.46	0.19	2.84
2040	2.21	0.47	0.22	2.90
2045	2.53	0.69	0.21	3.43
2050	2.84	0.92	0.20	3.97
2055	2.81	0.93	0.22	3.96
2060	2.70	0.93	0.23	3.85
2065	2.59	0.91	0.24	3.74
2070	2.53	0.91	0.24	3.68

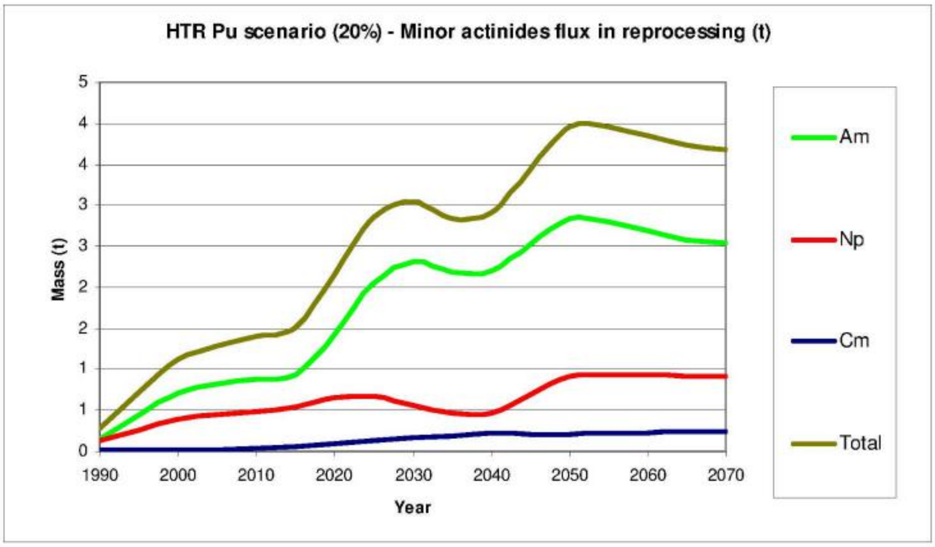

Figure 9

HTR PU scenario (20%) -– Minor actinides mass in irradiated fuel and separated stocks (t)

Year	Am	Np	Cm	Total
1990	3.2	3.5	0.3	7.0
2000	12.4	8.4	0.9	21.8
2010	27.3	14.4	2.2	44.0
2020	45.0	21.0	3.7	69.7
2030	66.0	28.5	5.5	100.0
2040	93.3	35.7	7.7	136.7
2050	120.3	43.1	9.1	172.4
2060	149.2	50.7	11.2	211.1
2070	177.6	58.6	13.1	249.3

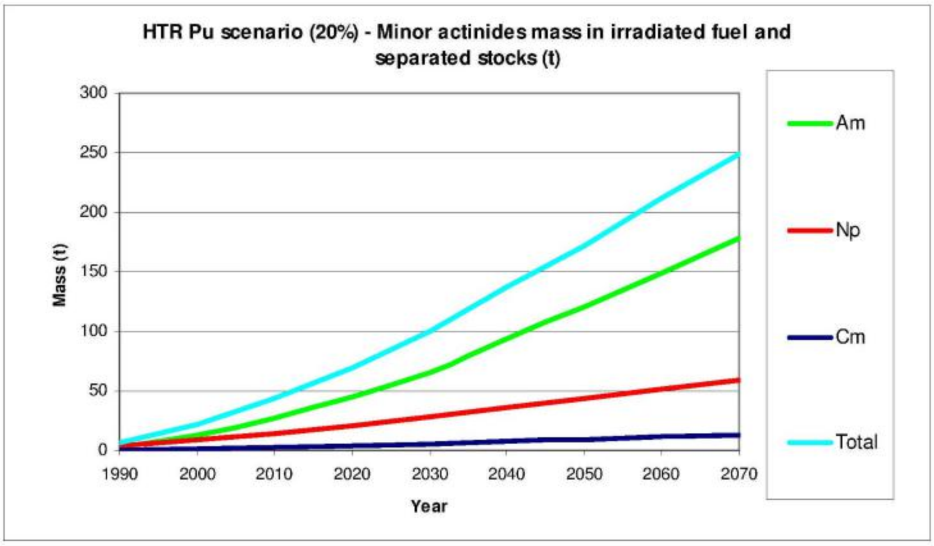

Figure 10

HTR PU scenario (20%) –– Annual and cumulated natural Uranium needs (t)

Year	Annual needs (t)	Cumulated needs (t)
1990	6284	8.13E+04
1995	8341	1.29E+05
2000	7926	1.70E+05
2005	8081	2.10E+05
2010	7978	2.50E+05
2015	7346	2.89E+05
2020	7286	3.26E+05
2025	7017	3.61E+05
2030	6748	3.96E+05
2035	6688	4.29E+05
2040	6688	4.62E+05
2045	6688	4.96E+05
2050	6688	5.29E+05
2055	6688	5.63E+05
2060	6688	5.96E+05
2065	6688	6.30E+05
2070	6688	6.46E+05

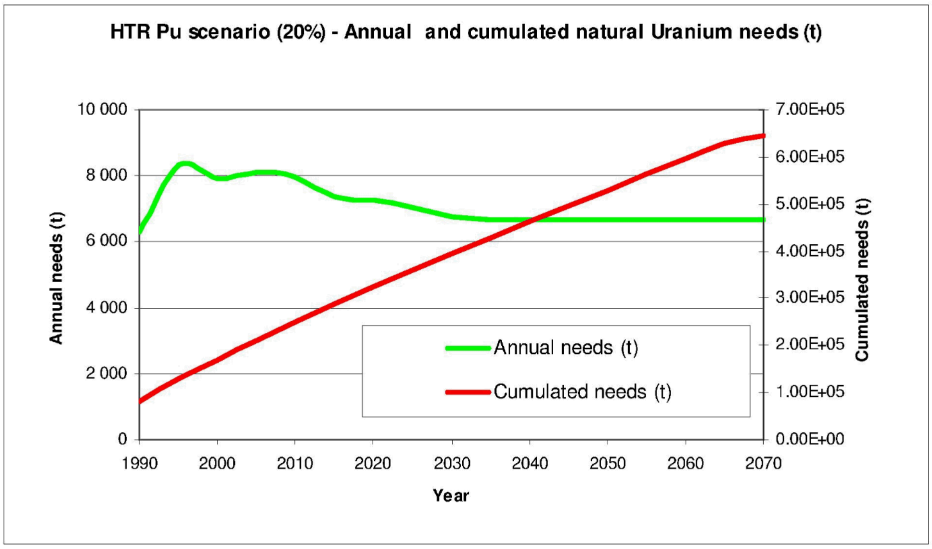

Figure 11

HTR PU scenario (20%) –- Annual and cumulated SWU needs

Year	Annual needs (10^6SWU)	Cumulated needs (10^6SWU)
1990	4.42	59.2
1995	5.75	86.6
2000	5.63	115.2
2005	5.97	143.9
2010	6.06	174.0
2015	5.63	204.0
2020	5.59	232.1
2025	5.38	259.4
2030	5.17	285.7
2035	5.13	311.4
2040	5.13	337.0
2045	5.13	362.7
2050	5.13	388.3
2055	5.13	413.9
2060	5.13	439.6
2065	5.13	465.2
2070	5.13	490.9

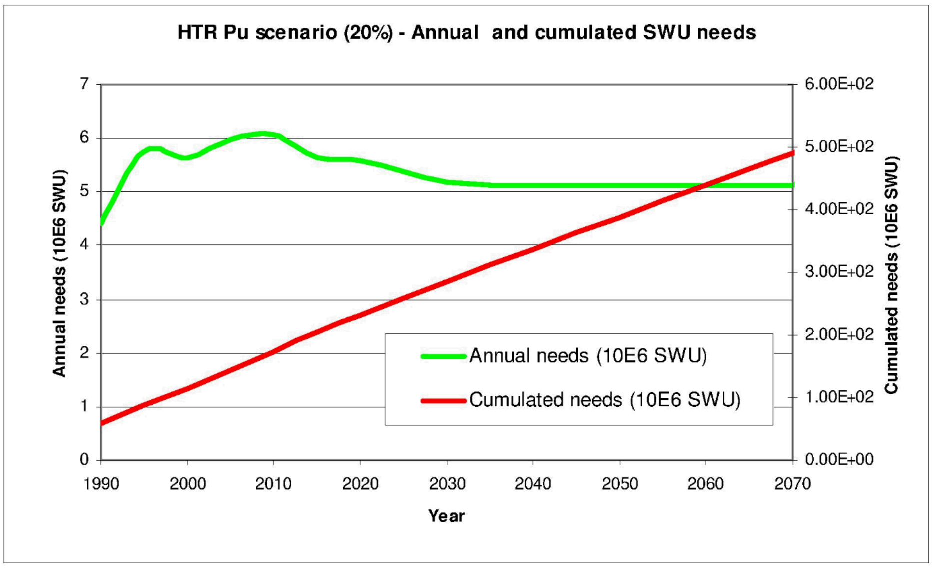

Figure 12

HTR PU scenario (20%) –– Annual flux and inventory for reprocessed Uranium (t)

Year	Annual flux	inventory
1990	308	1.18E+03
1995	627	3.31E+03
2000	913	7.36E+03
2005	984	1.22E+04
2010	937	1.70E+04
2015	849	2.15E+04
2020	900	2.58E+04
2025	837	3.02E+04
2030	663	3.39E+04
2035	546	3.68E+04
2040	549	3.95E+04
2045	717	4.27E+04
2050	897	4.69E+04
2055	911	5.14E+04
2060	906	5.59E+04
2065	896	6.05E+04
2070	821	6.48E+04

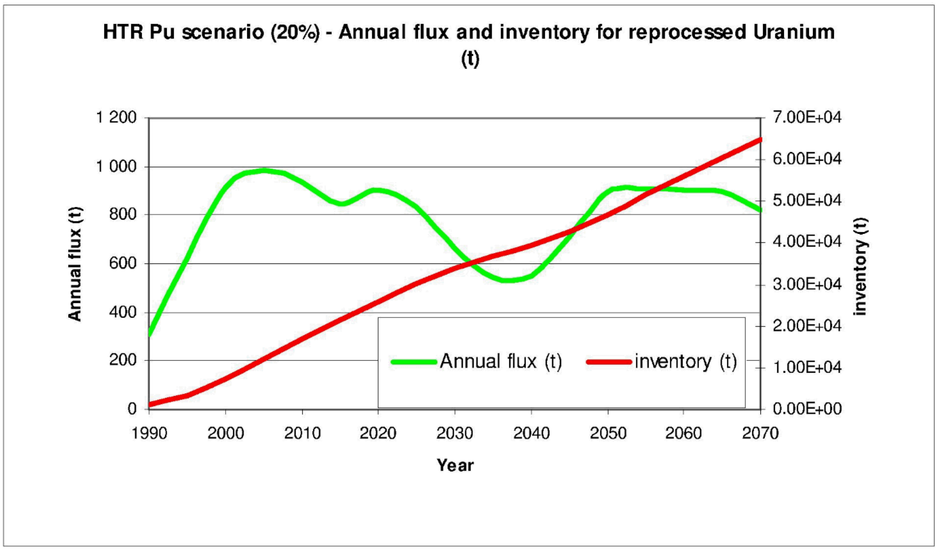

Figure 13

HTR PU scenario (20%) -– Annual flux and inventory for depleted Uranium (t)

Year	Annual flux	inventory
1990	5.59E+03	7.54E+04
1995	7.19E+03	1.10E+05
2000	6.92E+03	1.44E+05
2005	6.57E+03	1.77E+05
2010	6.57E+03	2.10E+05
2015	6.63E+03	2.42E+05
2020	6.60E+03	2.75E+05
2025	6.38E+03	3.07E+05
2030	6.12E+03	3.38E+05
2035	6.03E+03	3.68E+05
2040	6.03E+03	3.98E+05
2045	6.03E+03	4.28E+05
2050	6.03E+03	4.59E+05
2055	6.03E+03	4.89E+05
2060	6.03E+03	5.19E+05
2065	6.03E+03	5.49E+05
2070	6.03E+03	5.79E+05

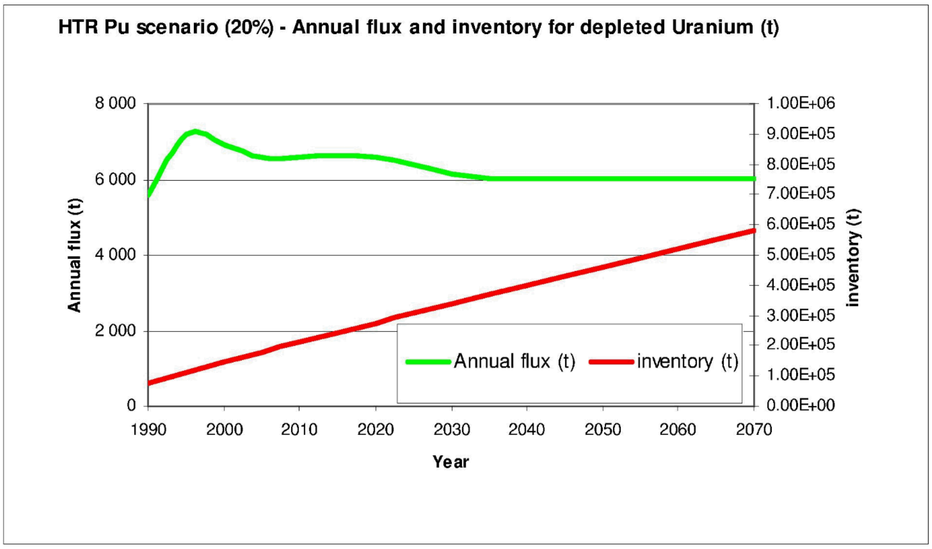

Figure 14

13. ANNEX 3 : HTR PU (17%)

HTR PU (17%) scenario - Energy production by fuel type (TWhe)

Year	UOX	MOX	HTR	Total
1990	291	9	0	300
1995	339	11	0	350
2000	364	36	0	400
2005	350	50	0	400
2010	351	49	0	400
2015	351	49	0	400
2020	351	49	0	400
2025	348	40	11	400
2030	332	0	66	398
2035	332	0	68	400
2040	332	0	68	400
2045	332	0	68	400
2050	332	0	68	400
2055	332	0	68	400
2060	332	0	68	400
2065	332	0	68	400
2070	332	0	68	400

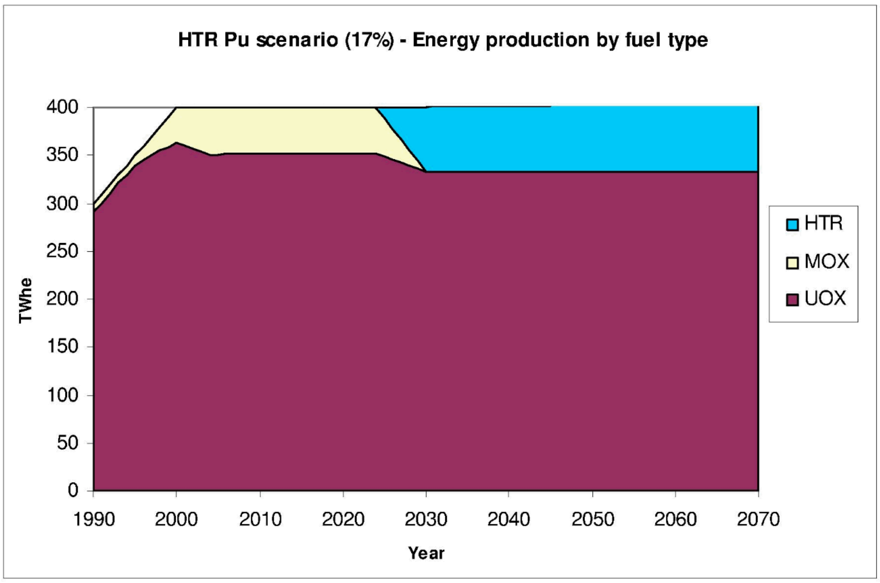

Figure 1

HTR PU scenario (17%) - Plutonium available in irradiated fuel stocks (t)

Year	HTR	UOX	MOX
2000	65.2	9.1	0.0
2005	69.7	25.0	0.0
2010	70.7	49.7	0.0
2015	68.7	79.2	0.0
2020	66.2	108.0	0.0
2025	63.6	119.4	0.1
2030	73.4	113.9	4.1
2035	94.4	100.5	20.0
2040	116.5	72.4	46.6
2045	136.4	31.0	73.4
2050	141.8	4.9	88.6
2055	129.7	0.0	93.8
2060	111.3	0.0	101.0
2065	93.1	0.0	113.9
2070	76.1	0.0	129.9
2075	63.1	0.0	146.8
2080	54.0	0.0	162.9
2085	46.2	0.0	174.4
2090	38.7	0.0	181.7
2095	31.2	0.0	188.4
2100	25.8	0.0	193.2

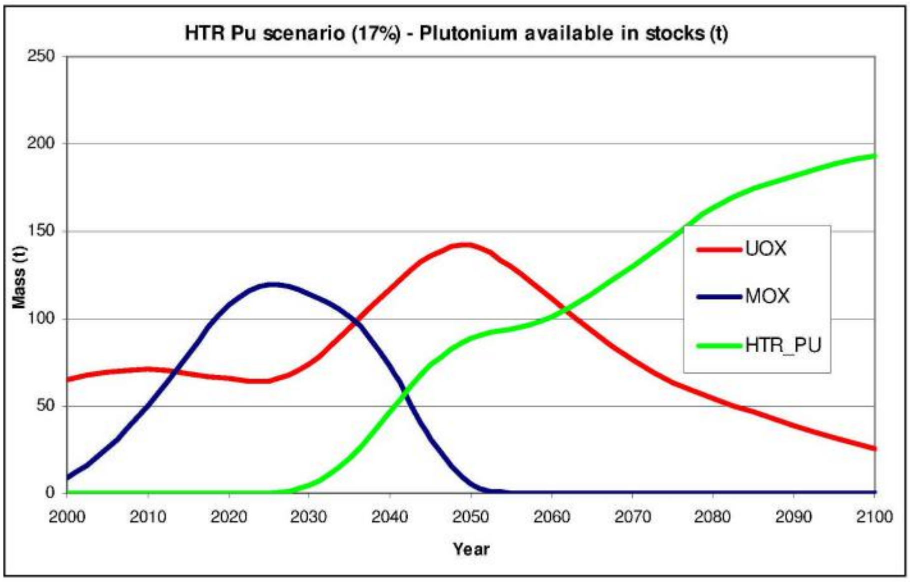

Figure 2

HTR PU scenario (17%) – Content and average Pu quality for fresh MOX assemblies

Year	Pu Content (%)	Pu quality (%)
2010	8.0	67.1
2020	8.9	64.3
2030	9.6	61.9

HTR PU scenario (17%) - Average Pu quality for fresh HTR-Pu assemblies

Year	Pu quality (%)
2 025	57.1
2 030	56.9
2 040	55.3
2 050	53.3
2 060	51.3
2 070	51.4
2 080	51.9
2090	51.7
2100	51.7

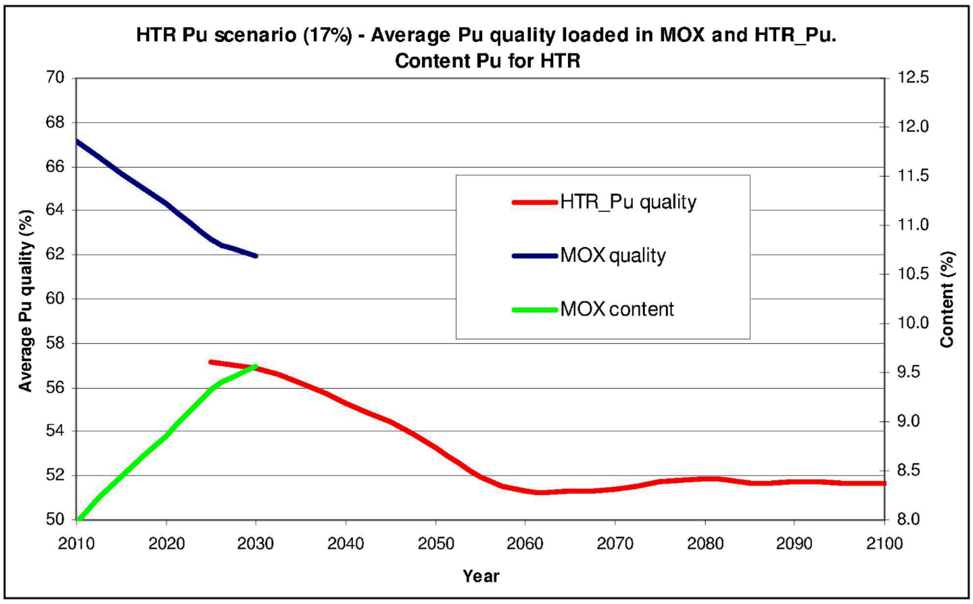

Figure 3

HTR PU scenario (17%) – Nuclear park Pu stocks (t)

Year	Plants	Reactors	Stocks	Total	Total (Pu+Am1)
2000	19.4	48.8	137.7	205.8	211.6
2005	16.8	66.8	162.1	245.8	254.1
2010	17.9	58.4	203.2	279.5	291.0
2015	18.8	75.2	216.3	310.3	325.1
2020	20.0	77.2	241.6	338.8	357.4
2025	30.5	83.9	251.8	366.2	386.8
2030	25.7	84.8	266.4	376.9	397.3
2035	25.7	56.2	294.3	376.2	398.2
2040	25.7	54.8	296.2	376.7	401.1
2045	25.8	54.8	296.4	377.0	404.1
2050	28.7	57.6	291.3	377.6	406.7
2055	32.5	60.6	283.8	376.9	405.2
2060	32.5	64.2	278.3	375.0	402.8
2065	32.6	64.2	276.0	372.8	400.8
2070	32.6	64.2	273.3	370.1	399.1
2075	29.0	64.2	274.2	367.3	398.2
2080	29.0	58.8	276.9	364.7	398.2
2085	29.1	58.7	274.3	362.0	397.7
2090	29.2	58.7	272.0	360.0	397.3
2095	29.2	58.8	270.1	358.0	396.9
2100	29.2	58.8	268.3	356.3	396.6

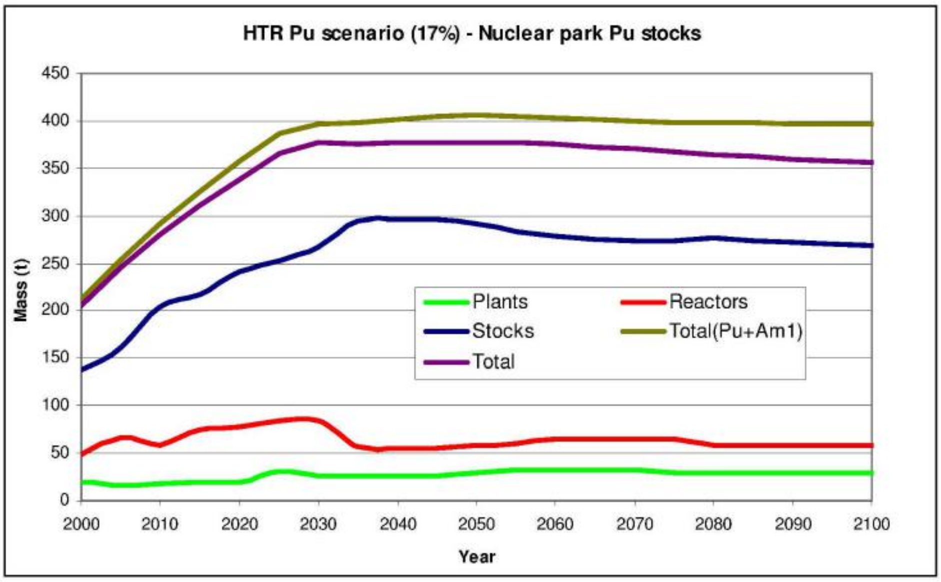

Figure 4

HTR PU scenario (20%) – Fuel reprocessing requirements (t)

Year	UOX	MOX	HTR (excluding graphite)
1990	290.2	0.0	0.0
1995	656.9	0.0	0.0
2000	956.3	0.0	0.0
2005	1032.9	0.0	0.0
2010	988.1	0.0	0.0
2015	901.4	0.0	0.0
2020	901.6	39.2	0.0
2025	719.1	119.7	0.0
2030	471.3	168.1	0.0
2035	367.6	157.5	0.0
2040	347.4	148.9	0.0
2045	439.0	116.2	2.2
2050	711.2	49.9	7.6
2055	942.2	0.0	11.9
2060	965.5	0.0	12.2
2065	961.3	0.0	12.2
2070	919.5	0.0	11.6
2075	855.9	0.0	10.8
2080	808.7	0.0	10.2
2085	797.9	0.0	10.1
2090	796.1	0.0	10.1
2095	796.0	0.0	10.1

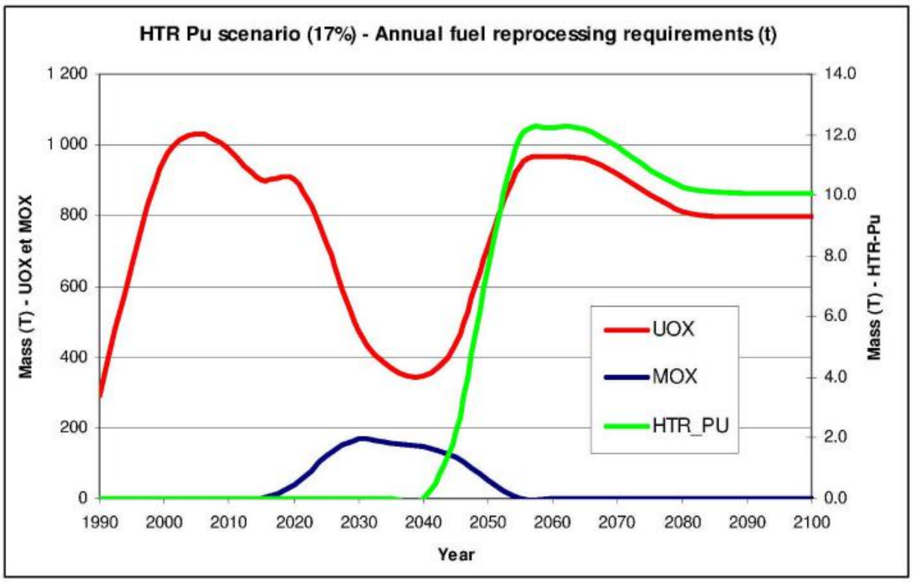

Figure 5

HTR PU scenario (17%) – Reprocessed Pu

Year	Reprocessed Pu for MOX (t)	Reprocessed Pu for HTR (t)	Total reprocessed Pu (t)
2 010	8.8	-	8.8
2 020	9.7	-	9.7
2 025	7.8	4.3	12.1
2 030	1.8	12.8	14.6
2 040	-	12.7	12.7
2 050	-	13.8	13.8
2 060	-	16.1	16.1
2 070	-	16.1	16.1
2080	-	14.4	14.4
2090	-	14.2	14.2
2100	-	14.2	14.2

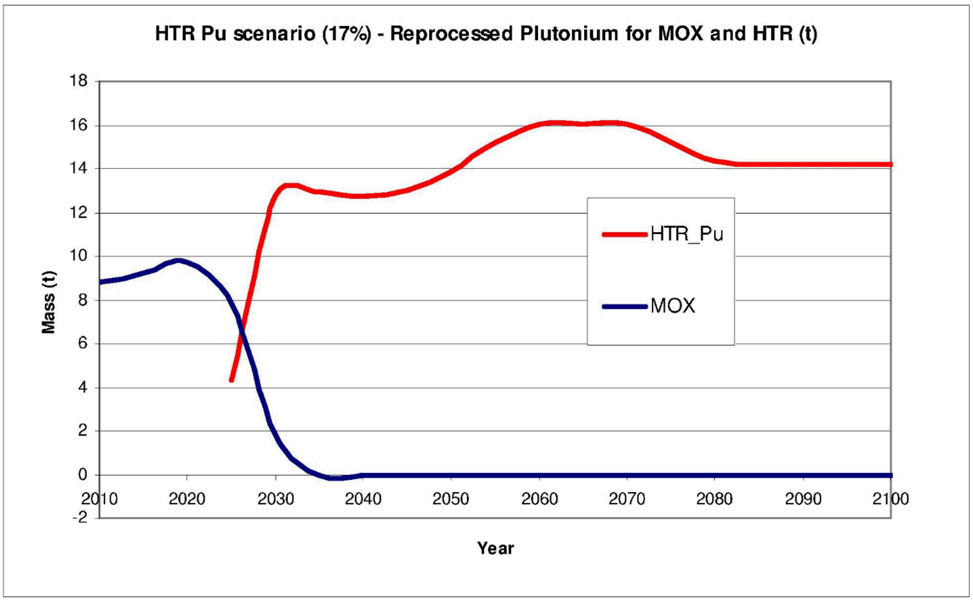

Figure 6

HTR PU scenario (17%) — Annual fuel fabrication requirements (t)

Year	UOX	MOX	HTR
1990	865.2	30.3	0.0
1995	1171.5	77.1	0.0
2000	1032.3	118.7	0.0
2005	943.8	135.6	0.0
2010	828.0	120.0	0.0
2015	786.0	118.4	0.0
2020	718.7	106.9	0.0
2025	704.2	74.0	8.8
2030	686.7	24.7	12.2
2035	680.6	0.0	12.8
2040	680.6	0.0	12.8
2045	680.6	0.0	13.1
2050	680.6	0.0	14.1
2055	680.6	0.0	15.4
2060	680.6	0.0	16.1
2065	680.6	0.0	16.1
2070	680.6	0.0	15.9
2075	680.6	0.0	15.0
2080	680.6	0.0	14.2
2085	680.6	0.0	14.2
2090	680.6	0.0	14.2
2095	680.6	0.0	14.2
2100	680.6	0.0	14.2

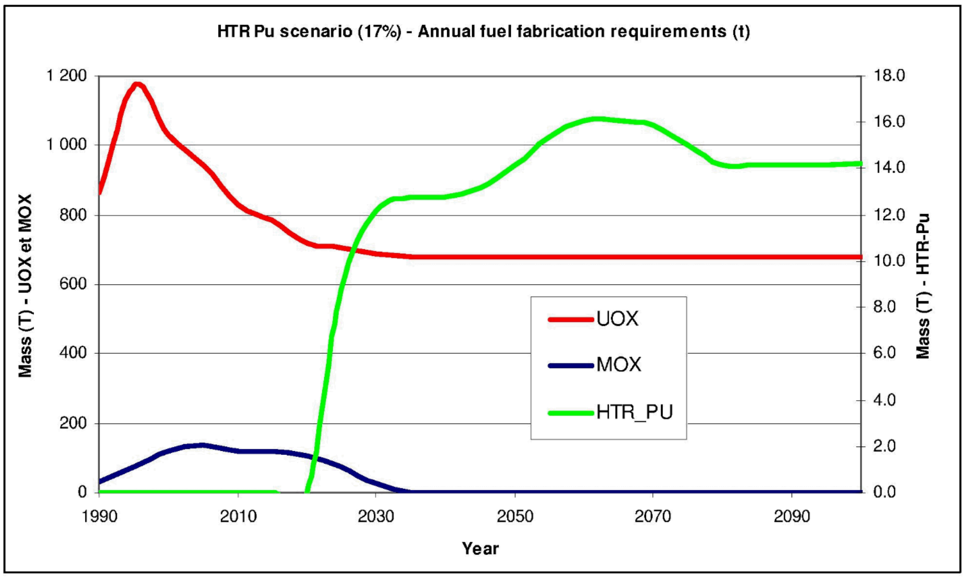

Figure 7

HTR PU (17%) scenario -- Waste storage requirements for irradiated fuel (t)

Année	UOX	MOX	HTR
1990	9414	0	0
1995	10813	218	0
2000	11789	527	0
2005	11371	1007	0
2010	10609	1550	0
2015	9847	2115	0
2020	8976	2579	0
2025	8541	2678	13
2030	9243	2381	39
2035	10779	1840	96
2040	12416	1135	159
2045	13938	449	219
2050	14360	68	258
2055	13422	0	276
2060	12005	0	292
2065	10593	0	311
2070	9279	0	332
2075	8275	0	355
2080	7578	0	378
2085	6969	0	399
2090	6392	0	420
2095	5815	0	440
2100	5395	0	455

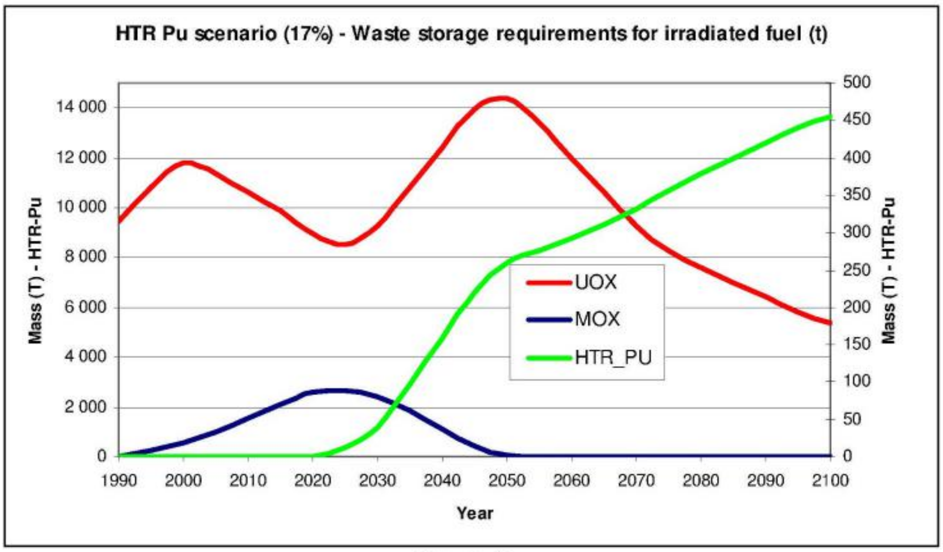

Figure 8

HTR PU scenario (17%) — Minor actinides flux in reprocessing (t)

Année	Am	Np	Cm	Total
1990	0.15	0.13	0.01	0.29
1995	0.44	0.27	0.02	0.72
2000	0.70	0.39	0.02	1.11
2005	0.82	0.45	0.03	1.30
2010	0.88	0.49	0.04	1.41
2015	0.94	0.53	0.05	1.52
2020	1.34	0.64	0.08	2.06
2025	1.85	0.63	0.11	2.59
2030	2.04	0.49	0.13	2.67
2035	1.97	0.41	0.15	2.53
2040	1.97	0.39	0.17	2.52
2045	2.14	0.47	0.17	2.78
2050	2.61	0.71	0.17	3.49
2055	2.98	0.91	0.18	4.07
2060	2.99	0.93	0.20	4.12
2065	2.91	0.92	0.21	4.03
2070	2.75	0.88	0.20	3.83
2075	2.58	0.82	0.20	3.59
2080	2.50	0.77	0.19	3.46
2085	2.50	0.77	0.19	3.46
2090	2.50	0.77	0.18	3.45
2095	2.49	0.77	0.18	3.44
2100	2.48	0.77	0.18	3.43

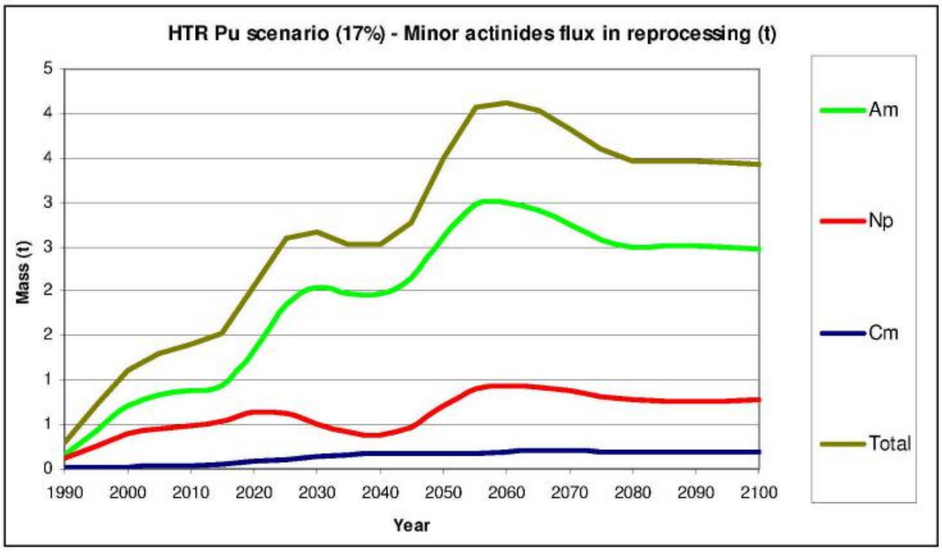

Figure 9

HTR PU scenario (20%) — Minor actinides mass in irradiated fuel and separated stocks (t)

Year	Am	Np	Cm	Total
1990	3.2	3.5	0.3	7.0
2000	12.4	8.4	0.9	21.8
2010	27.3	14.4	2.2	44.0
2020	45.0	21.0	3.7	69.7
2030	66.0	28.5	5.5	100.0
2040	92.6	35.9	7.3	135.8
2050	119.1	43.5	8.4	171.0
2060	147.2	51.3	9.8	208.4
2070	177.5	59.5	11.3	248.3
2080	208.0	68.1	12.5	288.5
2090	236.9	77.0	13.9	327.7
2100	264.4	86.2	15.0	365.6

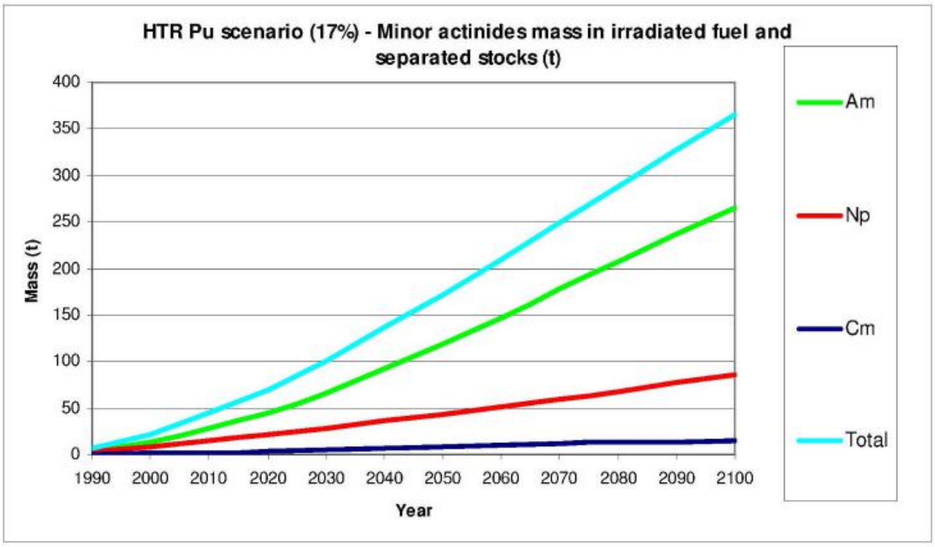

Figure 10

HTR PU scenario (17%) — Annual and cumulated natural Uranium needs (t)

Year	Annual needs (t)	Cumulated needs (t)
1990	6290	8.13E+04
1995	8341	1.29E+05
2000	7926	1.70E+05
2005	8081	2.10E+05
2010	7978	2.50E+05
2015	7346	2.89E+05
2020	7309	3.26E+05
2025	7142	3.62E+05
2030	6976	3.97E+05
2035	6939	4.32E+05
2040	6939	4.66E+05
2045	6939	5.01E+05
2050	6939	5.36E+05
2055	6939	5.70E+05
2060	6939	6.05E+05
2065	6939	6.40E+05
2070	6939	6.75E+05
2075	6939	7.09E+05
2080	6939	7.44E+05
2085	6939	7.79E+05
2090	6939	8.13E+05
2095	6939	8.48E+05
2100	6939	8.73E+05

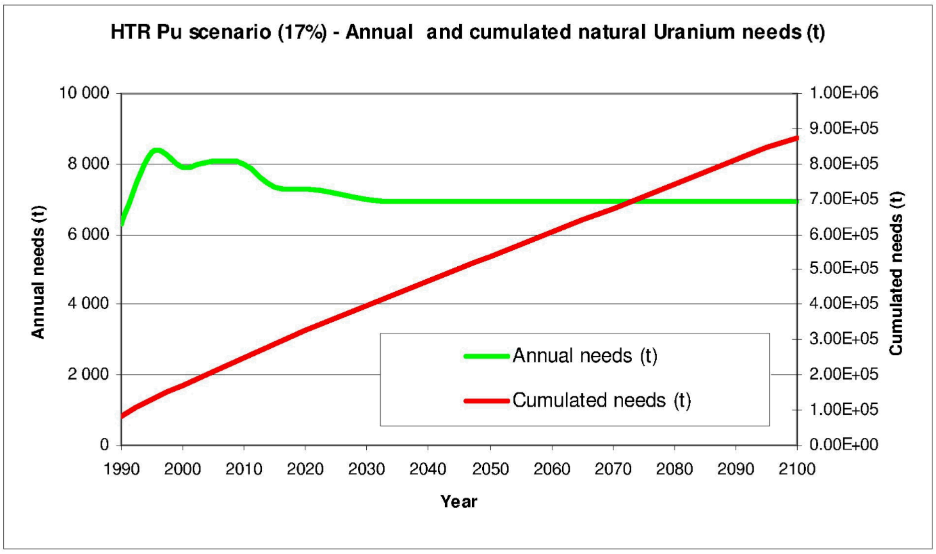

Figure 11

HTR PU scenario (17%) –– Annual and cumulated SWU needs

Year	Annual needs (10^6 SWU)	Cumulated needs (10^6 SWU)
1990	4.42	59.2
1995	5.75	86.6
2000	5.63	115.2
2005	5.97	143.9
2010	6.06	174.0
2015	5.63	204.0
2020	5.60	232.1
2025	5.48	259.8
2030	5.35	286.8
2035	5.32	313.4
2040	5.32	340.0
2045	5.32	366.6
2050	5.32	393.2
2055	5.32	419.8
2060	5.32	446.4
2065	5.32	473.0
2070	5.32	499.6
2075	5.32	526.2
2080	5.32	552.8
2085	5.32	579.4
2090	5.32	606.0
2095	5.32	632.6
2100	5.32	652.0

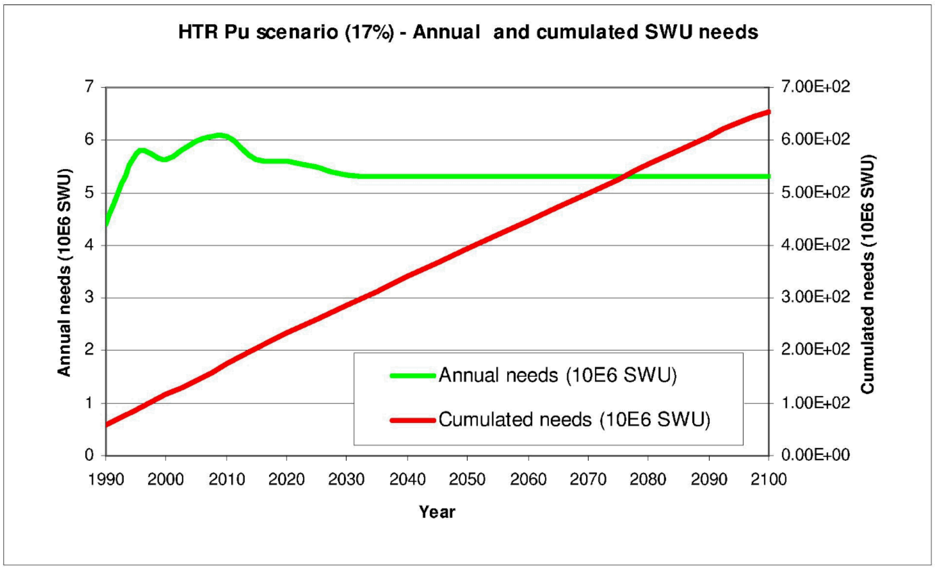

Figure 12

HTR PU scenario (17%) -– Annual flux and inventory for reprocessed Uranium (t)

Year	Annual flux	inventory
1990	308	1.18E+03
1995	627	3.31E+03
2000	913	7.36E+03
2005	984	1.22E+04
2010	937	1.70E+04
2015	849	2.15E+04
2020	880	2.58E+04
2025	777	3.00E+04
2030	586	3.33E+04
2035	478	3.58E+04
2040	451	3.81E+04
2045	511	4.05E+04
2050	704	4.36E+04
2055	870	4.77E+04
2060	891	5.21E+04
2065	887	5.66E+04
2070	849	6.09E+04
2075	790	6.50E+04
2080	746	6.88E+04
2085	736	7.25E+04
2090	735	7.61E+04
2095	735	7.98E+04
2100	734	8.25E+04

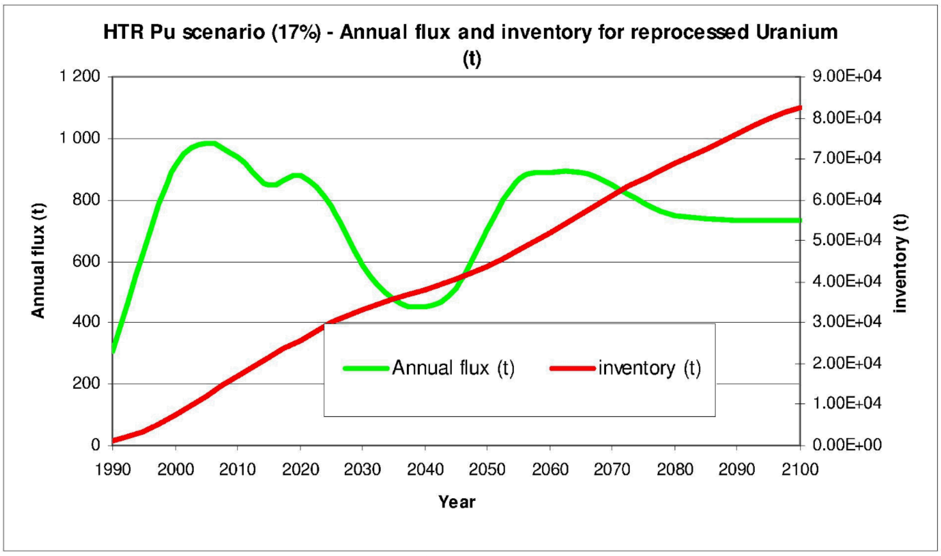

Figure 13

HTR PU scenario (17%) --- Annual flux and inventory for depleted Uranium (t)

Year	Annual flux	inventory
1990	5.59E+03	7.54E+04
1995	7.19E+03	1.10E+05
2000	6.92E+03	1.44E+05
2005	6.57E+03	1.77E+05
2010	6.57E+03	2.10E+05
2015	6.63E+03	2.42E+05
2020	6.61E+03	2.75E+05
2025	6.48E+03	3.07E+05
2030	6.31E+03	3.39E+05
2035	6.26E+03	3.70E+05
2040	6.26E+03	4.02E+05
2045	6.26E+03	4.33E+05
2050	6.26E+03	4.64E+05
2055	6.26E+03	4.95E+05
2060	6.26E+03	5.27E+05
2065	6.26E+03	5.58E+05
2070	6.26E+03	5.89E+05
2075	6.26E+03	6.21E+05
2080	6.26E+03	6.52E+05
2085	6.26E+03	6.83E+05
2090	6.26E+03	7.14E+05
2095	6.26E+03	7.46E+05
2100	6.26E+03	7.68E+05

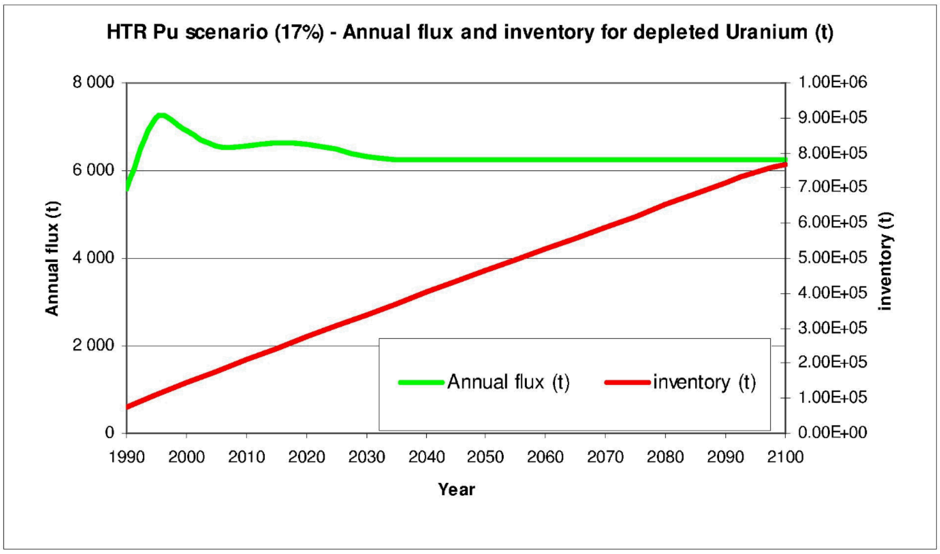

Figure 14

cea	DEN	DER	NT – SPRC - LECy 2004/318		A/43
			RÉFÉRENCE	INDICE	PAGE

FICHE DE VÉRIFICATION DU DOCUMENT

TITRE DU DOCUMENT : SCENARIO STUDIES WITHIN A NUCLEAR PARK COMPOSED OF PWRs AND GTMHR-TYPE HTRs USING REACTOR-GRADE PLUTONIUM

Rédacteur : P.BOURDOT

Domaines* de la Vérification	Résultats **		
1) Vérification scientifique et technique			
Les documents de références et les documents applicables sont-ils mentionnés ?	Oui	Non	SO
L'étude s'appuie-t-elle sur une analyse de l'état de l'art ?	Oui	Non	SO
Le problème est-il clairement posé ?	Oui	Non	SO
Les hypothèses sont-elles clairement définies ?	Oui	Non	SO
Les données sont-elles appropriées et validées ?	Oui	Non	SO
Les méthodes employées sont-elles justifiées et validées ?	Oui	Non	SO
Les ordres de grandeur sont-ils cohérents ?	Oui	Non	SO
Les conclusions sont-elles justifiées ?	Oui	Non	SO
2) Vérification de la clarté et de la cohérence d'ensemble			
Le Titre est-il explicite et pertinent ?	Oui	Non	
Le Résumé est-il autoporteur, clair et conclusif ?	Oui	Non	
Le Résumé est-il cohérent avec l'Introduction et la Conclusion ?	Oui	Non	
Les Mots Clés sont-ils pertinents et exhaustifs ?	Oui	Non	
L'Introduction indique-t-elle suffisamment : les objectifs contractuels, le contexte technique, les objectifs techniques précis, les enjeux, …	Oui	Non	
L'Introduction présente-t-elle l'articulation de la présentation ?	Oui	Non	
L'enchaînement des étapes de la présentation est-il compréhensible ?	Oui	Non	
La Conclusion précise-t-elle clairement le degré d'atteinte des objectifs contractuels ?	Oui	Non	
La Conclusion ouvre-t-elle des perspectives ?	Oui	Non	SO
3) Vérification des exigences de la PR1 G1 du MQ DER	Conformité		
Modèle de NT	C	NC	
Contenu des « cartouches » : page 1, page 2 et page courante	C	NC	
Plan du document et Pagination	C	NC	
Clarté de la mise en forme (traitement de texte)	C	NC	
Respect de l'orthographe et de la grammaire françaises	C	NC	
Formules, Figures, Tableaux, … (titres, unités, échelles, légendes, …)	C	NC	SO
Bilan de la Vérification			
Les modifications demandées ont toutes été prises en compte par le Rédacteur	Oui	Non	SO
Les modifications identifiées en PJ n'ont pas été suffisamment prises en compte par le Rédacteur et nécessitent l'arbitrage de l'Approbateur	Oui	Non	SO

**	C et Oui	Jugé Satisfaisant par le Vérificateur
**	NC et Non	Jugé Non Satisfaisant par le Vérificateur : modifications demandées au Rédacteur
**	SO	Jugé Sans Objet par le Vérificateur (la rubrique ne s'applique pas)

Nb de pages en PJ à la Fiche de Vérification :

Vérificateur : JY.DORIATH	**Domaines* : 1, 2 et 3**	**Date :**	**Visa :**

* En standard, le Vérificateur couvre les 3 domaines. Cette cellule peut faciliter la gestion des Vérificateurs multiples, pour s'assurer de cette couverture (chacun barre le domaine qu'il n'a pas couvert).

APPENDIX B

Original document

B. Bonin, D. Greneche, F. Carre, F. Damian & J.Y. Doriath, "*Utilisation/disposition of reactor-grade plutonum in HTRs*", Nuclear Technology 145, 266-274, March 2004; also presented as "*Prospective studies of HTR fuel cycles involving plutonium*", Proc. HTR 2002, Petten, the Netherlands;15 pages.

The original document has also been inserted into the SINTER database as HTR-N1 external/support document no. **HTR-N1-03/06-X-3.3.1-1**.

UTILISATION/DISPOSITION OF REACTOR-GRADE PLUTONIUM IN HTR'S

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COGEMA, Direction de la Recherche et du Développement
F.CARRE, F. DAMIAN and J.Y. DORIATH,
CEA Direction de l'Energie Nucléaire

ABSTRACT

High Temperature Gas Cooled reactors (HTRs) are able to accommodate a wide variety of mixtures of fissile and fertile materials without any significant modification of the core design. This flexibility is due to an uncoupling between the parameters of cooling geometry, and the parameters which characterize neutronic optimisation (moderation ratio or heavy nuclide concentration and distribution).

Among other advantageous features, an HTR core has a better neutron economy than a LWR because there is much less parasitic capture in the moderator (capture cross section of graphite is 100 times less than the one of water), in internal structures, and in fission products (because of a harder spectrum).

Moreover, thanks to the high strengthof the coated particles, HTR fuels are able to reach very high burn-ups, far beyond the possibilities offered by other fuels (except the special case of molten salt reactors).

These features make HTRs especially interesting for closing the nuclear fuel cycle and *stabilizing the plutonium inventory*.

A large number of fuel cycle studies are already available today, on 3 main categories of fuel cycles involving HTRs : i) High enriched uranium cycle, based on thorium utilization as a fertile material and HEU as a fissile material; ii) Low enriched uranium cycle, where only LEU is used (from 5% to 15 %); iii) Plutonium cycle based on the utilization of plutonium only as a fissile material, with (or without) fertile materials.

Plutonium consumption at high burnups in HTRs has already been tested with encouraging results under the DRAGON project and at Peach Bottom. To maximize plutonium consumption, recent core studies have also been performed on plutonium HTR cores, with special emphasis on weapon-grade plutonium consumption. In the following, we complete the picture by a core study for a HTR burning reactor-grade plutonium. Limits in burnup due to core neutronics are investigated for this type of core.

With these limits in mind, we study in some detail the Pu cycle in the special case of a reactor fleet made of a mixture of LWRs and HTRs. It is reasonable to assume that if HTRs are to be deployed on an industrial scale, they will co-exist during a long period of time with already existing LWRs. The present paper investigates the symbiotic behaviour of LWRs producing plutonium, and of HTRs burning it.

1. Introduction

High Temperature, Gas-Cooled reactors (HTRs) have several fundamental features which distinguish them from other types of reactors, and provide significant operational advantages.

HTRs are able to accommodate a wide variety of mixtures of fuels without any significant modification of the core design. This flexibility is due to an uncoupling between the parameters of cooling geometry, and the parameters which characterize neutronic optimization (that is moderation ratio or heavy nuclide concentration and distribution). In fact, it is possible to modify the packing fraction of coated particles in the fuel within the graphite matrix without changing the dimensions of the fuel elements. Furthermore, different kinds of particles with various kernel diameters, containing either fertile or fissile isotopes may be accomodated in the same fuel. Other physical reasons favour the much better adaptability of HTRs with regard to the fuel cycle in comparison with reactors using moderators in the liquid form, such as LWRs. An illustration of that is the void coefficient which limits the plutonium content of PWR MOX fuels and which is not a constraint for HTRs. It is to be noted also that an HTR core has a better neutron economy than a LWR because there is much less parasitic capture in the moderator (capture cross section of graphite is 100 times less than the one of water), in internal structures, and in fission products (because of a harder spectrum).

Finally it must be noted that HTR fuels are able to reach very high burn-ups, which are far beyond the possibilities offered by other thermal reactors (except the particular case of molten salt reactors). This capability allows for essentially complete plutonium fission without recycle and minimizes the proliferation risk in the use of this fuel form.

2. - A classification of fuel cycles in HTRs

Numerous studies have been carried out in the past to assess and compare merits and drawbacks of all solutions which may be considered in HTRs, and which depend on:

- the type of fissile material (U233, U235, Plutonium), fertile material (Th232, U238) , andenrichments,
- utilization conditions in the reactor: moderation ratio, frequency of reloads, fraction of the core replaced at each cycle, distribution of fertile and fissile materials among various categories of particles, etc.
- fissile material recycling strategy

A large number of results are available today [1], and these can be summarized by considering 3 main categories of fuel cycles :

1) High Enriched Uranium (HEU) cycle based on thorium utilization as a fertile material, and high enriched uranium (typically 93 %) as a fissile material

2) Low Enriched Uranium (LEU) cycle where only enriched uranium is used (from 5 % to 15 %)

3) Plutonium cycle based on the utilization of plutonium only as a fissile material, with (or without) fertile materials.

For completeness, it is to be noted that a kind of "hybrid" cycle called MEU (involving a mixture of medium enriched uranium (20%) with thorium) has also been considered. In the following, we shall discuss in more detail each of the three categories mentioned above.

2.1 – The HEU + Th cycle

Thorium, being the fertile material utilized in this cycle, generates U233, which is by far the best fissile isotope for thermal spectrum reactors. Furthermore, there are probably more thorium than uranium resources, and its utilization as a fertile isotope in reactors has been extensively studied, particularly for HTRs.

For these reasons, the HEU + Th cycle was considered as the reference cycle at the very beginning of HTR development in both USA and Germany. As a result, 4 HTR prototype power reactors having operated in the past (AVR [2] and THTR in Germany, Peach Bottom and Fort Saint Vrain in USA) were first loaded with fuel containing thorium in various forms such as carbides, oxides, and single thorium particles or mixtures with uranium.

The main advantage of this cycle is to significantly reduce uranium consumptions (typically from 10 % for an open cycle to a factor 2 or more when high conversion ratios are used in a closed cycle). Another advantage, which was not underlined in the past but which may become an important argument, is the significant reduction of minor actinide production if U233 is recycled in reactors, as would occur in reactors operated with Th-U233 cycles.

On the other hand, the competitiveness of an HEU cycle is questionable today, all the more so because there is a large uncertainty on thorium costs, since the market for this material is very limited. The main technical hurdle for the development of the HEU cycle comes from U233 recycling. The difficulty arises from the significant energetic γ emission of some daughter products of U232 (70 year half life), which is produced alongwith U233. This harmful emission essentially requires a remote fabrication process of U233 fuels. Technically this operation is certainly feasible with modern technologies, but significant R&D effort would be necessary to industrialize it and to ensure its profitability.

2.2 – The LEU cycle

The LEU cycle uses uranium with a minimum enrichment of 5 to 6 %, which is more than the highest enrichments usually utilized in other current thermal reactors such as LWRs (for HTR's, the uranium enrichment for LEU cycles usually ranges from 5 % to 15 %). This is due to a rather diluted and homogeneous uranium distribution in HTR fuels which favours U238 resonance captures (self shielding effect is reduced). This greater neutron absorption must be compensated for by a higher enrichment.

The LEU cycle was studied during the 60's and 70's in USA and Germany as well as in England and in France. Some LEU fuels were loaded in the European experimental reactor DRAGON. Furthermore, Germany decided in the 80's to select this fuel for their future projects, and this kind of fuel is also the one used for the South-African PBMR project [3,4]. Japan has also selected this fuel as well for their HTTR experimental reactor, which is in operation today [5].

2.3 Plutonium fuel cycles with or without thorium

From a physics standpoint, the interest of plutonium use in HTRs comes from flexible features already discussed above. It is known that plutonium isotopes have very large capture resonances near the thermal range of the neutron spectrum. This is the reason why plutonium reactivity and evolution as function of time heavily depends upon its initial concentration and distribution in the fuel (because of self-shielding effect mentioned above). In that respect, a HTR provides a large margin to the designer for optimising fuel cycle characteristics.

The idea to use plutonium as the only fissile material but still with thorium as a fertile material was considered very early in the 60's within the framework of the DRAGON project [6]. The General Atomics company took up the studies in 1968 in a program with Edison Electric Institute. This program was carried out up to the manufacturing of a test fuel element and its irradiation in the Peach Bottom HTR.

To maximize plutonium consumption, more recent studies have been performed on plutonium HTR cores with no fertile material at all. This solution has been particularly considered in the framework of weapon-grade plutoniumdisposition [7,8]. For the reasons already discussed above, only HTRs offer such a possibility (a part from fast neutron reactors for which it seems theoretically feasible to design core containing only plutonium).

As far as net plutonium consumption is concerned, performances claimed for this type of fuel cycle are remarkable. For example, if we refer to joint studies between GA and MINATOM on what they call the "PC-MHR" (Plutonium Consumption – Modular Helium Reactor), plutonium consumption reaches 90 kg/TW(e)hr[1]. As a guide, an EPR (European Pressurized Reactor) loaded with 100% MOX fuel could theoretically consume 65 kg/TW(e)hr. One can also compare with a Fast Neutron Reactor operating in"under-breeding" mode which could achieve a theoretical consumption of 80 kg/TW(e)hr, provided that advanced fuel containing 45% of plutonium are developed (see French "CAPRA" program).

From this short overview, we can draw the following main conclusions:

In spite of its potential advantages, the HEU + Th cycle appears to be handicapped because of proliferation concerns. However it should be worthwhile to carry out further studies in order to better assess its potential benefits with regard to other questions, such as minor actinide generation, which has taken much importance in recent years.

The LEU cycle benefits from the largest experience but needs an uranium enrichment beyond 5% which is the upper limit for most existing fuel cycle facilities in many countries. However, the centrifuge enrichment technology, which is presently emerging as the reference technology for uranium enrichment, is especially well suited to fulfill the HTR needs. Thanks to its intrinsic

[1] It is easy to verify this figure by using a 50 % efficiency of the plant, and elementary fission energy release of 210 MeV. In fact, the net plutonium consumption reaches about 100 kg/TWhe due to the the formation of americium and curium from the plutonium by neutron capture.

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flexibility, it enables the production of uranium enriched in a wide range of grades with only minor modifications in the cascade arrangement.Therefore, production of enriched uranium for LEU HTRs on an industrial scale is already possible in the existing centrifuge plants, and should be even easier in the future ones. The development of new fuel fabrication plants, needed to manufacture HTR fuel particles and fuel elements, is probably a more delicate issue.

Thorium use is not specific to HTRs even though they are better adapted than other reactors to take advantage of thorium properties, because of a much higher resonance absorption rate of thorium in an HTR fuel. Recycling of U233 however would require more industrial experience.

For plutonium consumption, HTRs are, without doubt one of the best types of reactors. Only fast neutron reactors may compete in this domain, but at the cost of as much, or more, development as HTRs. Taking into account the acquired background on HTR fuels, it seems that there is no technological hurdle to achieve expected performances of plutonium consumption. Moreover, 20 years ago, the context was not the same and in particular, questions such as plutonium consumption or long-term waste management were not so acute. Therefore, it is worthwhile to reconsider this option in light of these new challenges.

3. Burning reactor-grade plutonium in HTRs. A fuel cycle scenario.

3.1 Assumptions

In this paper, we studied the fuel cycle for a plausible scenario describing the progressive introduction of Pu-burning HTRs in a fleet initially composed of LWRs.

In this preliminary step of the study, we did not try to treat the subject exhaustively. Indeed, we restricted ourselves to the assumption that the HTRs are exclusive Pu burners, and that the Pu comes from the LWRs.

Fuel cycle studies in steady state regime are of limited interest, because time constants for the introduction of new nuclear reactors are always very long. For the long-term future, fast neutron reactors might possibly become available before a steady state regime for any existing reactor fleet can be established. For the sake of plausibility, the scenario in this paper has thus been studied in transient regime, and covers only the mid-term future.

We are interested mainly in the plutonium balance, because Pu is an important energetic resource, and because it is the major contributor of the radiotoxic fuel inventory.

Hypotheses underlying the scenario under study are as follows :

-The studied scenario is deemed to be realistic for the next 50 years. However, in order to gain some insight into the asymptotic behavior of the reactor fleet, the studied time window has been extended to 100 years, that is between 2000 and 2100.

-The total electric power produced by the reactor fleet is kept constant during this period.

-We start with a realistic initial total plutonium inventory in 2025, supposed to be representative of the French situation at that time, namely 400 tons.

-We assume a gradual replacement of existing LWRs by Pu-burning HTRs. The rate of replacement is 2.1 % per year, between years 2025 and 2035. At that time, the reactor fleet is stabilized, and 21.25 % of the total installed electric power is produced by HTRs (Fig. 1) (This figure has been chosen because, as will be seen later, it ensures a quasi-stabilization of the total Pu inventory).

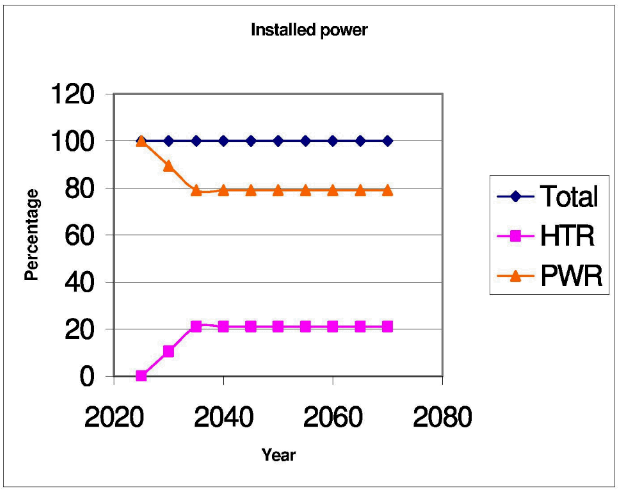

Fig. 1: Composition of the reactor fleet, vs time

-We assume that MOX fuel is used in 42% of the LWR fleet during the early years of the period under study (until 2025). After that date, we assume that the LWRs become exclusive UOX burners (noMOXing in LWRs after 2025). However, all the UOX fuel burnt in the LWRs is still processed to produce the Pu fuel needed for HTRs (in the following, this fist-generation plutonium will be referred to as "Pu1"). All the MOX fuel is reprocessed as well, in order to feed HTRs with its second-generation plutonium (Pu2).

-The burnup of the UOX fuel in LWRs is assumed to be 55 GW.d/t, with a fuel renewed by one fifth every year. This corresponds to a net production of plutonium of 25 kg/TWhe.

-Since the high burnup achievable in HTRs does not encourage multiple recycling, we assume a once-through cycle of Pu in HTRs (discharged plutonium then becomes a waste).

-We assume a net consumption of plutonium in HTRs of 100 kg/TWhe. The Pu burnup achievable in a thermal HTR has been assumed to be 500 GW.d/t. As will be justified in section 4, this is probably a rather conservative value.

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3.2 Results of the fuel cycle study in this scenario

Stabilization of Pu inventory is achieved around year 2030. This Pu inventory has two components : in and out of the reactors. The plutonium inventory out of the reactors is plotted vs time in fig. 2. The mass of Pu discharged from the HTRs grows linearly with time, while the Pu mass still available for HTR fuel fabrication decreases linearly after year 2040.

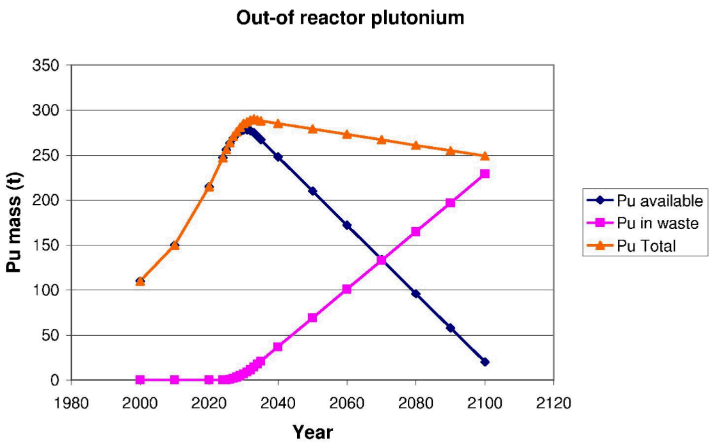

Fig 2: Evolution of the out-of-reactor Pu inventory for a fleet producing 400 TWhe/year

It can be seen that the plutonium mass available for HTR fuel fabrication almost vanishes around year 2100. We reach here the limits of a realistic scenario, since other types of reactors might possibly enter into the fleet long before this date.

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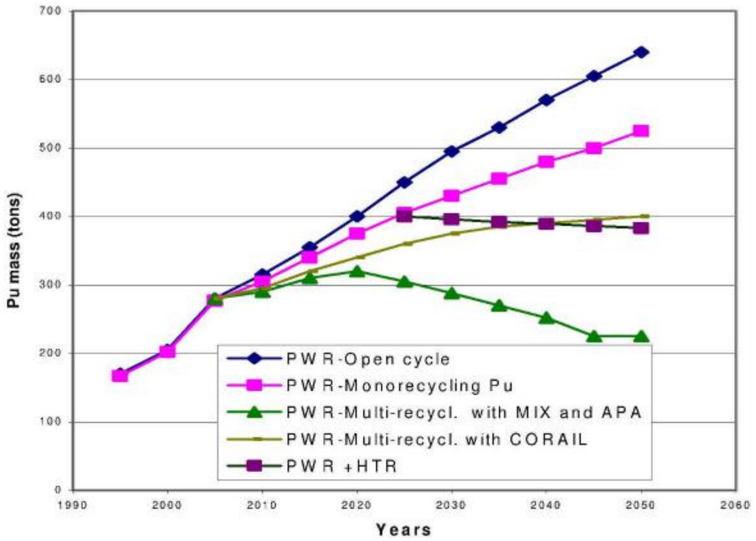

Fig. 3 Total plutonium inventory for a reactor fleet producing 400 TWhe/year

During the period under study in the present scenario, other fuel cycle options could be envisaged for light water reactors. For example, advanced fuels like CORAIL and APA, whose goal is precisely to enhance the Pu consumption in LWRs [9], could be introduced. It is thus interesting to compare

these options, which assume a pure LWR reactor fleet, with oursymbiotic scenario LWR+HTR. The total Pu inventory versus time is plotted in Fig. 3 for all these options.

It can be seen here that for Pu burning, HTRs compare favorably to LWRs. The stabilization of Pu inventory is possible with LWRs only if advanced fuels are used and with multirecycling. A mixed fleet of LWRs and HTRs easily achieves the same result with standard fuel (for LWRs) and without multirecycling. However, the comparison between the various options is not straightforward, and needs a few comments. One should note that the isotopic composition of the Pu left as "waste" by the LWR + HTR symbiotic fleet is so degraded that the proliferation risk becomes negligible (Table 1).

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Isotopic composition of the discharged plutonium	PWR/UOX 42 GWd/t	HTR/ Pu 575 GWd/t
Pu 238	2.7	10
Pu 239	54.5	8
Pu 240	22.9	23
Pu 241	11.7	24
Pu 242	7	35
% Pu fissile	**66.2**	**32**

Table 1. The plutonium isotopic composition of a typical spent UOX fuel (Pu1) and of a typical spent HTR fuel.

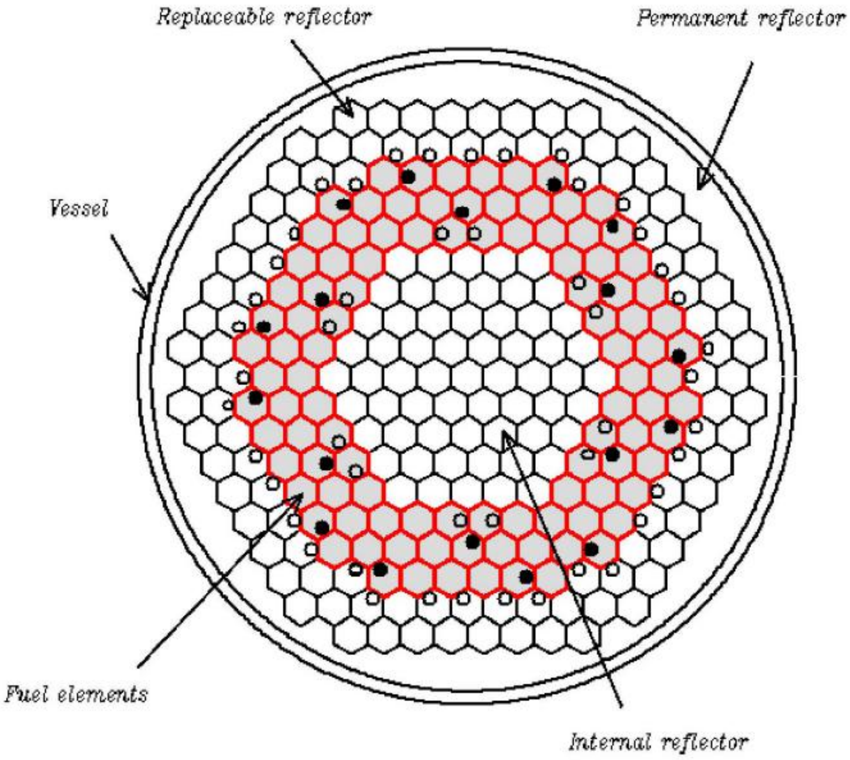
Moreover, whereas the advanced fuel discharged from LWRs may need some further conditioning, the Pu discharged from HTRs is under the form of coated microspheres, which can be considered already as a suitable waste form for interim storage or for final disposal. However, it must be noted that the deep burning of plutonium produces large quantities of minor actinides. Typically, the production of 1 TWhe by fission of 1st –generation plutonium results in the production of 12 kg of americium and curium. Calculations of the decay heat and radiotoxicity of spent fuel are under way.

4. Core studies for a Pu-burning HTR. Maximum Pu burnup achievable in a HTR

A key assumption in the above fuel cycle studies is the Pu burnup achievable in HTRs. The burnup limitation can come from two main causes : the stabilityof the fuel particles under irradiation, and the neutronic behaviour of the core. The fuel particle themeselves do not seem to be a severe limitation, since burnups as high as 750 GW.d/t have been achieved without degradation of the fuel particles in previous experiments [6]. This encouraging –but isolated- result must be confirmed by new experiments.

In order to assess the feasibility of HTRs with an "allplutonium" core, preliminary studies, mainly based on a fuel element calculation, [10, 11, 12] were carried out at CEA in the special case of the Gas Turbine Modular Helium-cooled Reactor (GT-MHR) 600 MWth General Atomics concept. The annular core geometry of the GT-MHR (fig. 4) was selected to maximize the power density and still permit passive core heat removal while maintaining reasonable fuel temperatures during accident conditions.

Fig. 4 GT-MHR 600 MWth core



Cycle name	Plutonium origin#	Pu_f/Pu_t
Pu1	PWR 3,7 % (U5/U) 42 GWd/t - 1/4	66.2 %
Pu2	Second generation MOX-EPR 60 GWd/t	50.15 %
WPu	Weapons grade	94.6 %

#PWR, EPR : Pressurized Water Reactor and European Pressurized Reactor

Table 2 : Plutonium isotopic compositions

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4.1 Categories of Pu fuels investigated

The Pu composition considered in this study is of course the first-generation Pu coming from the spent LWR UOX fuel (Pu1), but we thought it would be worthwhile to perform core calculations for other Pu compositions as well (Table 2). MOX burning in LWRs generates a second generation of plutonium (Pu2) that has also been considered in the present core study. Plutonium coming from the dismantling of nuclear warheads has also been studied (WPu).

4. 2 Computer codes and methodology for core calculation

For the following calculations, the French reactor physics code system SAPHYR developed at CEA has been used [13, 14]. It is composed of several codes: *APOLLO2* (transport), *CRONOS2* (diffusion-transport), *FLICA4* (3D thermal hydraulics), which are interconnected.

4. 3 Plutonium fuel cycle characteristics

Fuel element analyses: reactivity margin and burnable poison impact

Figure 5 shows the evolution of infinite multiplication coefficient for Pu1, for two different masses of Pu loaded in the core, and with or without burnable poison (Erbium). On the one hand, it should be stressed that compared to a similar fuel depletion without erbium (Pu1–701 kg), the fuel with poison presents an initial reactivity reduction of around 9000 pcm which almost disappears towards 600 GWd/t, corresponding to the loss of 90 % of ^{167}Er. The cycle lengths are however comparable.

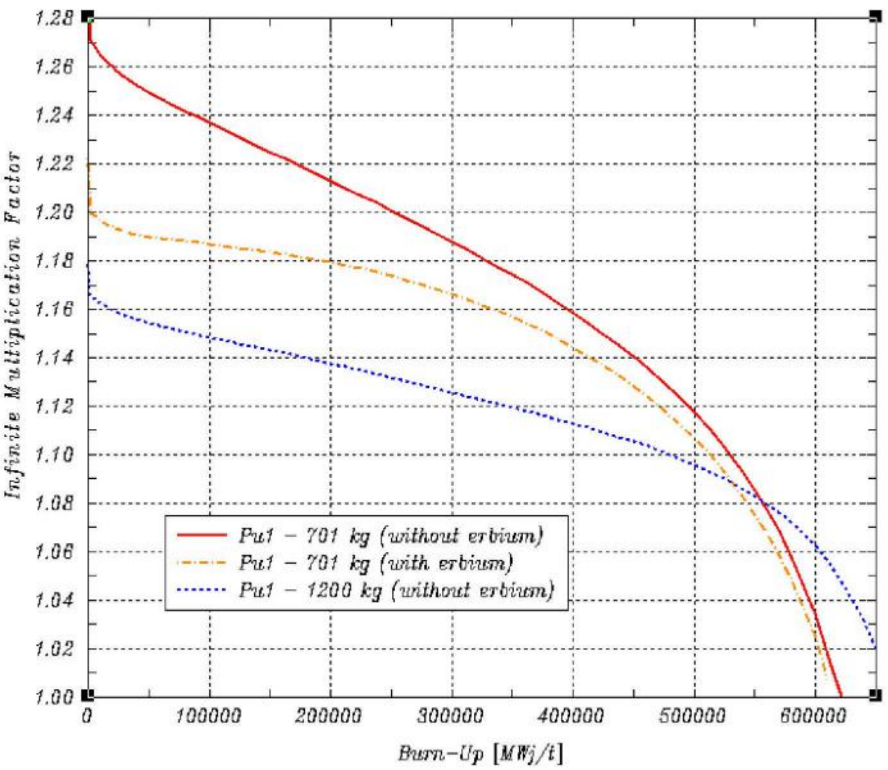

Fig. 5 k_{inf} in evolution

This important feature of the burnable poison equivalent to that observed with ^{10}B allows adjusting

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the initial reactivity of the different fuel cycle without changing the cycle lengths. On the other hand, the increase of the plutonium loaded in the fuel element leads to a spectrum hardening that induces a decrease of the reactivity margin at the beginning of cycle (increase of the resonance capture). Then, it is possible to adjust the initial reactivity by adjusting the plutonium loaded into the core. Nevertheless, we should not forget that the presence of the Erbium in fuel elements may play an important part in the core behaviour with regard to the negative reactivity feedback especially with highly enriched plutonium.

Fuel element temperature coefficient (infinite medium)

The results presented hereafter (Table 3) gather the average temperature coefficient (Doppler and moderator coefficient) between a cold state ($T_{fuel} = T_{moderator}$ = 20 °C) and an arbitrary nominal state (T_{fuel} = 900 °C / $T_{moderator}$ = 500 °C). The calculations have been performed for various types of fuel in order to evaluate both isotopic and core loading effects on this reactivity balance.

Fuel	WPu - 701 kg with Er	Pu1 – 701 kg without Er	Pu1 - 1200 kg without Er	Pu1 - 1800 kg without Er	Pu2 - 1200 kg without Er
Doppler coefficient (pcm/K)					
BOC	– 1.33	– 2.76	– 3.49	– 3.70	– 3.99
EOC	– 1.09 (700 GWd/t)	– 0.98 (625 GWd/t)	– 0.92 (650 GWd/t)	– 1.14 (650 GWd/t)	– 1.61 (550 GWd/t)
Moderator temperature coefficient (pcm/K)					
BOC	– 5.33	– 2.29	– 1.91	– 1.46	– 1.83
EOC	+ 8.60 (700 GWd/t)	+ 8.15 (625 GWd/t)	+ 4.47 (650 GWd/t)	+ 1.74 (650 GWd/t)	+ 4.02 (550 GWd/t)

Table 3 : **Fuel element temperature coefficient at the beginning of cycle (BOC) and at the end (EOC)**

Finally, these calculations show that regardless of the plutonium quality, the Doppler coefficient remains negative throughout the fuel cycle. This is probably the most important factor for the pilotability and safety of the reactor. On the other hand, it should be noted that the moderator temperature coefficient becomes less negative with irradiation, and even becomes positive at the end of the fuel cycle. This is due to the modification of the isotopic composition of the core under irradiation, which induces in turn a thermalization of the neutron spectrum; The influence of the temperature on the reactivity is more important for a thermalized spectrum. This effect also occurs albeit to a lesser extent for LEU cores, and is probably of minor concern, given the large thermal inertia of the moderator, but a more detailed safety study would be needed to ascertain the viability of the "all plutonium cores", for the three types of Pu composition and for the burnups mentioned above.

Residual decay heat

For various types of fuel, Figure 6 shows detailed evolution of the stored energy during a Loss of Coolant accident. This energy comes from the core decay heat of the GT-MHR-600 MWth calculated after a reactor shutdown occurring at the end of cycle. Due to the difference in fission yield between the Pu isotopes, the calculation shows some differences in decay heat depending on the plutonium composition and loading. More important, for high Pu loading, the calculated values are significantly higher than for a typical "all uranium" core. The result will be an increase of the maximum temperature reached by the Pu core in the course of the accident. No detailed thermal calculation has been undertaken so far but our first guess is that this temperature increase is still acceptable for a Pu fuel element.

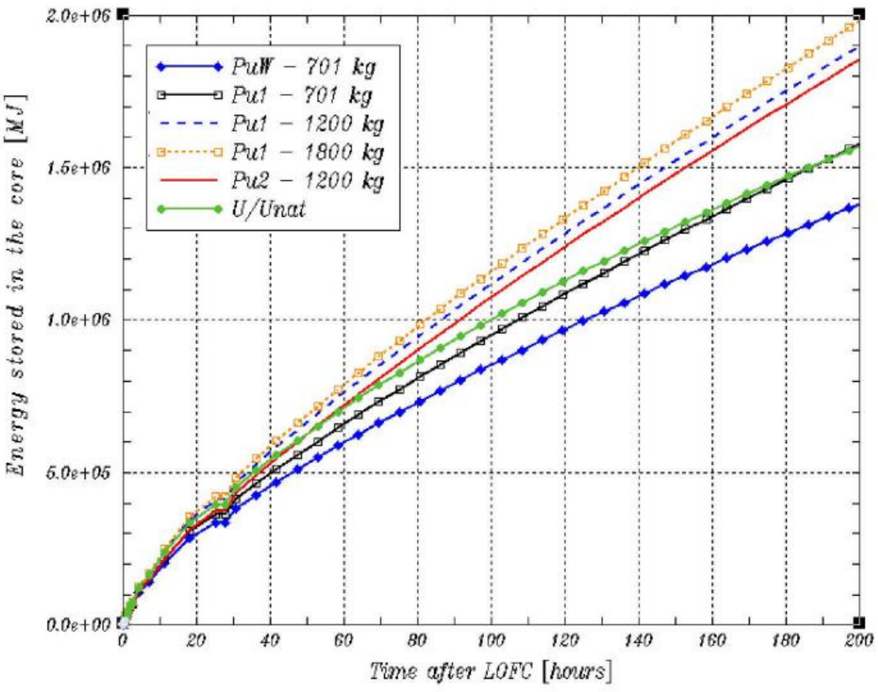

Fig. 6 Cumulated core decay heat after a reactor shutdown

5. Conclusion

Core studies with a wide range of plutonium isotopic compositions suggest that High-Temperature Reactors might be able to use the plutonium as fuel with no major hurdle from the safety standpoint. For each plutonium composition, limits on the possible applications of long fuel cycle lengths have been assessed. Long cycles and high burnups are possible if fluences of about 12 n/kb (a factor 2 more than the common requirements) are technologically feasible. Nevertheless, more detailed core neutronic analysis and thermal calculations are necessary to assess the reactivity control aspects, to define the appropriate fuel management and to answer the issues related to power distribution, which are especially important in the case of the plutonium use.

The present study confirms that a symbiotic reactor fleet involving LWRs and Pu-burning HTRs might be a very effective way to stabilize the plutonium inventory while providing energy in safe and (hopefully) economical conditions.

However, it must be stressed that even though a rather large experience has already been gained in HTR fuels, significant R&D effort would still be necessary to perfect and qualify a high performance plutonium fuel on an industrial scale for this type of reactor.

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