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Scenario study of (V)HTR deployment as a heat source in European and world context

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End-User Requirements fOr industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply

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End-User Requirements fOr industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply

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Summary
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1. INTRODUCTION

The overall goal of this study is to assess the impact on nuclear resources (uranium, thorium) and on nuclear waste (minor actinides) of several potential scenarios of HTR deployment during the 21st century.

The scenarios that have been selected for this study consider HTR are introduced in an already existing fleet of nuclear plants. This already existing fleet of nuclear plants is assumed to produce some amount of electricity, depending on the studied scenario and the related hypothesis. In this frame, HTR are introduced not so much to provide some additional amount of electricity but as to provide some amount of industrial heat, alternatively to traditional means of heat production such as gas, oil and coke.

In other words, in this study, HTR are deployed additionally to some previously defined nuclear scenarios (called 'reference secanrios'); in all cases HTR deployements are motivated by substituting some conventional means by nuclear means of producing industrial heat; the impacts of HTR introduction are evaluated by the additional amounts of natural resources that are consumed and by the additional amounts of nuclear waste that are produced, in comparison with the equivalent amounts of natural resources and nuclear waste that are basically involved in the selected reference nuclear scenarios.

The reference nuclear scenarios are selected among two families of scenarios:
- European scenarios: data about electrical demand were taken from the study conducted in late 2000 by the Sustainable Nuclear Energy Technology Platform (SNE-TP), while data about non-electrical demand were taken from the IIASA-WEC studies;
- world scenarios: data were taken from the study conducted in late 1990 by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC);

Several variation HTR scenarios are studied by considering different HTR fuel types (UOx, Pu, U/Th) as well as different rhythms of HTR deployments for the 21st century. The conclusions are established by comparing the results obtained from all the variation scenarios.

2. ASSUMPTIONS AND RESOURCES

2.1 Uranium resources

Data about uranium resources that are used in this study are based on the OECD/NEA « Red Book » published in 2009 (Ref. [OECD/NEA, 2009]). This most recent publication indicates the following values:

- Identified conventional resources : this category consists of Reasonably Assured Resources (RAR) and Inferred Resources (IR). The total amount of these resources raises to **6.3 millions tons** for a recoverable cost up to USD 260/kgU (i.e. USD 100/lbU_3O_8);
- Undiscovered resources : this category consists of Prognosticated resources and Speculative resources. Both refer to resources that are expected to occur based on geological knowledge of previously discovered deposits and regional geological mapping. The total amount of these resources raises to **6.8 millions tons** for a recoverable cost up to USD 260/kgU (i.e. USD 100/lbU_3O_8).

2.2 HTR cogeneration features

HTR features used in the study are derived from the Chinese HTR-PM design and are summarized in the below table:

Parameter	Unit	HTR feature for cogeneration		
Core parameters				
Total thermal power	MWth	450		
Electrical power	MWe	68		
Heat power	MWth	315		
Electrical efficiency	%	15		
Heat efficiency	%	70		
Total efficiency	%	85		
Load factor	%	85		
Fuel parameters		UOx Ref. [van Heek, 2006]	Pu (2nd generation) Ref. [de Haas, 2003]	U/Th Ref. [Teuchert, 1986]
Burnup	GWd/tHM	80	449.8	100
Fresh fuel composition	%	U: 100 ^{235}U: 8.1 Pu: 0 Th: 0 MA: 0	U: 0 ^{235}U: 0 Pu: 100 Th: 0 MA: 0	U: 39.33 ^{235}U: 9.845 Pu: 0 Th: 60.67 MA: 0
Spent fuel composition	%	U: 88.2 ^{235}U: 1.266 Pu: 1.37 Th: 0 MA: 0.14 FP: 8.2	U: 0.181 ^{235}U: - Pu: 45.07 Th: 0 MA: 10.12 FP: 44.63	U: 32.15 ^{235}U: 8.018 Pu: 0.57 Th: 56.85 MA: 0.14 FP: 10.43
Irradiation duration	EFPD	1007	2880	872
Fuel batch number		10	10	10
Processing parameters				
Fabrication time	months	6		
Minimum cooling time after discharge	years	5		

Table 1: HTR features

The HTR feature related to efficiency (heat efficiency, electrical efficiency) is coming from the Paper #125 presented for the HTR-2010 congress (Ref. [Geschwindt, 2010]).

All the studied scenarios consider the reprocessing of LWR-UOx spent fuel. Plutonium that is retrieved from this reprocessing is then re-used into LWR-MOX. The energy provided by such a recycling is assumed to be comprised between 11% and 13.5% of the total energy provided by LWR fleet. The time the fuel is spending out of the core is assumed to be: 5 years for cooling and transportation operations, 0.5 year for reprocessing operations. These are minimum values, they can be greater if plutonium is not required as soon as it is available.

3. REFERENCE CASES

3.1 European case

3.1.1. European case modeling

The European nuclear reactor park has been analysed applying an integrated dynamic process modeling technique. Starting point for the analyses is the current nuclear reactor park in the 27 member states of the European Union (EU27), presented in figure 1. For the existing nuclear reactor park, the foreseen lifetime of each individual reactor is taken into account as well as the nuclear fuel cycle infrastructure. Furthermore, an energy demand scenario has been applied as input for the analyses, consisting of an electrical and a non-electrical part.
For the assessment of the nuclear fuel cycle strategies, the DANESS code ("Dynamic Analysis of Nuclear Energy System Strategies") version 4.0 [Van den Durpel 2008], was used to simulate the flows of fissile material, fresh fuel, spent fuel, high level waste as well as all intermediate stocks and fuel cycle facility throughput.

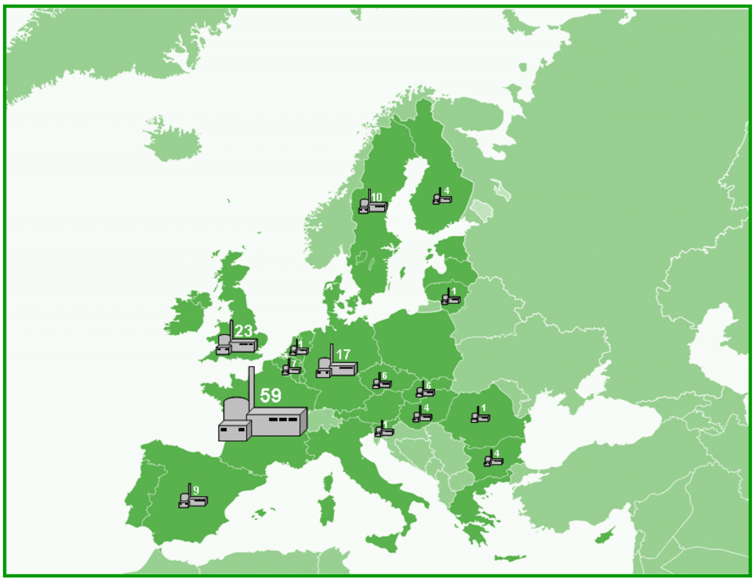


Fig. 1. Current nuclear reactor park in EU27 (152 reactors)

DANESS is based on a system dynamics model, using the iThink-software [IseeSystems, 2009], allowing to simulate the dynamic behaviour of systems including multiple components and to simulate and investigate the dynamic interdependence of these components interacting between each other via feedback loops. System dynamics software also provides an easy way of communicating the set-up of models and the outcome of the simulations while also providing a good framework for quality assurance and control of the models.
DANESS allows to simulate time-varying nuclear energy systems from cradle-to-grave and to support nuclear energy assessment processes from a technological, economic and environmental perspective. It produces quantities like mass flows and costs as a function of time, typically spanning time-periods of coming decades or century. Both resource and waste quantity development are being determined, for any combination of reactor systems and fuel cycles.

New reactors are introduced based on the energy demand and the economic and technological ability to build new reactors. The technological development of reactors and fuel cycle facilities is modeled to simulate delays in availability of technology by means of technological readiness levels (TRL) determined for the different reactor types. It is clear that such modeling does demand significant amounts of reactor and fuel cycle facility specifications (i.e. technical, economic and environmental attributes).

The architecture of the DANESS v4.0 code is depicted schematically in figure 2. A more detailed description of DANESS v4.0 can be found in [Van den Durpel 2008].

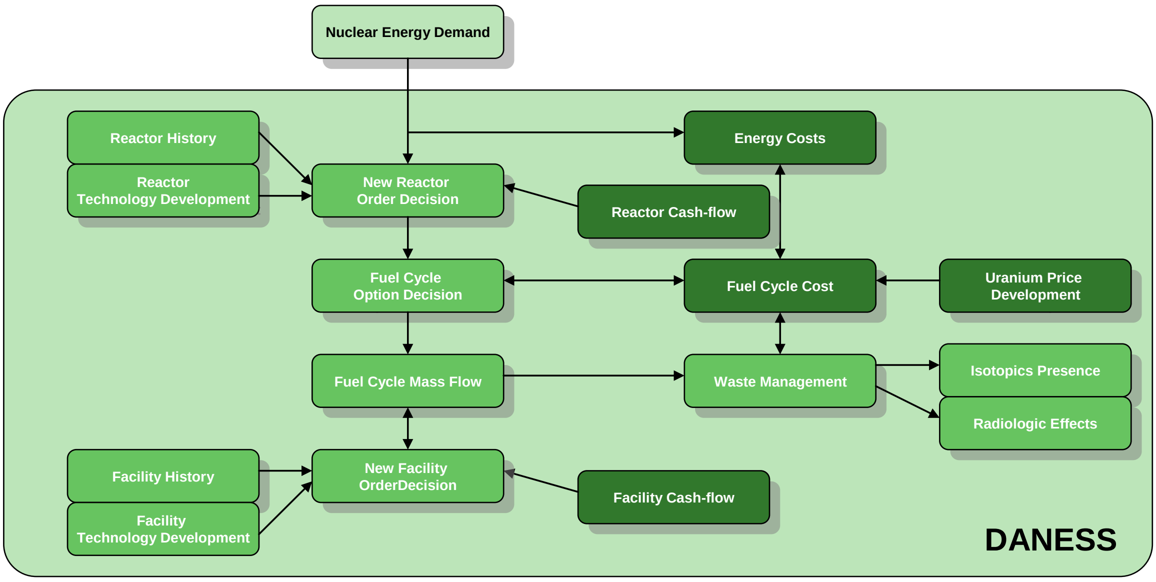


Fig. 2: Architecture of DANESS v4.0

3.1.2. European case demand data

The energy demand cases for the EUROPAIRS project consist of two parts: an electrical and a non-electrical one.

The electrical demand is taken from the SNE-TP Vision Report [SNE-TP, 2007], see fig. 3. It is a constant demand scenario, assuming that the absolute nuclear electricity demand will not rise or decline. This is a translation of the European situation of various countries with different energy policies: some expanding, some freezing and some phasing out their nuclear capacity.

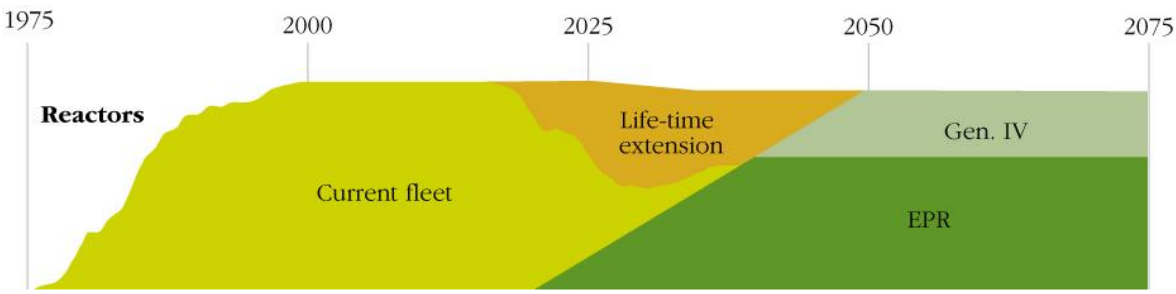


Fig. 3. Deployment of Gen III and Gen IV reactors [SNE-TP, 2007]

The non-electrical demand is taken from a study from the International Institute for Applied Systems Analysis (IIASA) and the World Economic Council (WEC) [IIASA WEC 1998]. For seven regions in the world, the final energy demand is estimated for the 21st century for ten energy carriers and six development scenarios. Also, the shares of the various resources for electricity production were estimated, including nuclear. For our study, the reference scenario B (business as usual) was selected. Two of the seven world regions concern Europe (west and east), so their data were added together. The energy carriers taken into account are electricity, hydrogen, methanol, district heat, oil and gas. Conservatively, the replacement of oil and gas by nuclear is expected to happen only in the energy-intensive energy sector, comprising 60% of the total [DG-TREN, 2007]. For the non-electric energy demand, the distribution over de energy carriers throughout the 21st century is shown graphically in fig. 4.

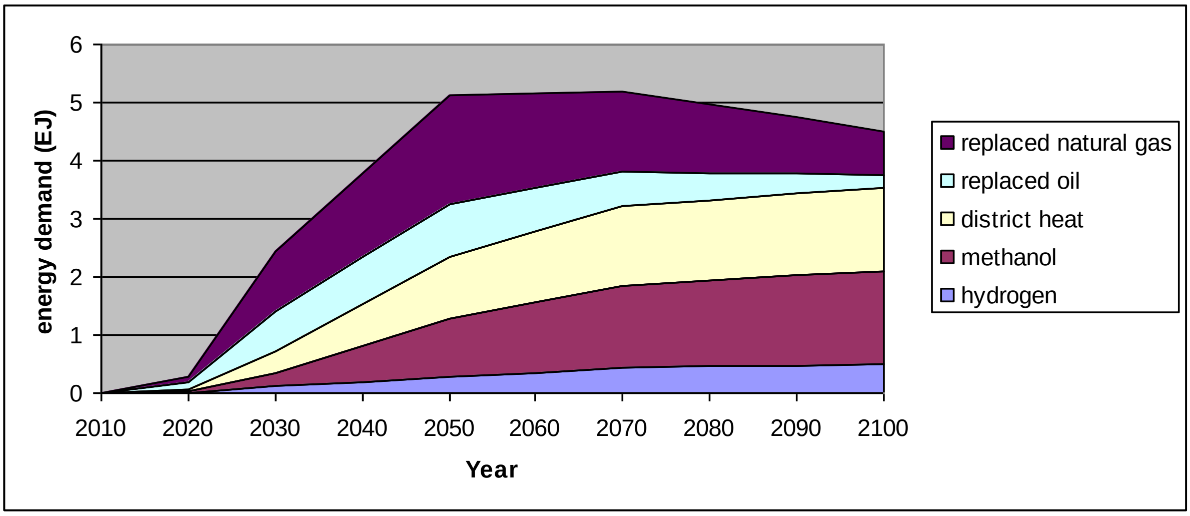


Fig. 4: Distribution of energy demand over non-electric energy carriers. [IIASA WEC 1998].

In order to model the nuclear cogeneration demand correctly, a reference industrial site has been selected as Chemelot in The Netherlands. The cogeneration plant and process steam parameters given in EUROPAIRS deliverable D2.1. Chemelot contains a 180 MWe natural gas-fired cogeneration plant, that is being replaced by a nuclear one in that study, producing sufficient amount of process steam for the Chemelot industrial site. An additional 90 MWe is drawn from the electrical grid.

Currently some industrial sites in Europe (like Chemelot) have gas-fired cogeneration, and some have not. All industrial sites are assumed to take on nuclear cogeneration. Those sites that had gas-fired cogeneration before, will now take more electricity from the grid: the gas-fired cogeneration plant produced 180 MWe, and the nuclear plant only 135 MWe (see chap. 2). On the other hand, the sites that didn't have cogeneration before will now take less electricity from the grid, as they have nuclear cogeneration now. We assume now that these two effects are offsetting each other, so there will not be any additional demand from the grid.
Therefore for the European case study it is assumed that:

- All electricity is delivered by the existing nuclear park and future LWR,
- All process heat is delivered by HTR on sites equivalent to Chemelot,
- The electricity delivered by the HTR stays on the industrial site; replaces fossil fuel of current cogeneration plants.

3.1.3. European case facility input data

The existing reactor park is modeled as five ‘average’ combinations of reactor and fuel types:

- AGR & Magnox: a 566 MWe reactor with 1.5% enriched UOx fuel,
- LWR with UOx fuel: a 1053 MWe reactor with 4.2% enriched UOx fuel,
- LWR with MOX fuel: a 1234 MWe reactor with 30% MOX fuel,
- VVER: a 551 MWe reactor with 3.1% enriched fuel,
- PHWR: a 706 MWe reactor with natural UOx fuel.

As a representative Generation III LWR for newbuild in the 21st century, the 1600 MWe EPR has been modeled, with 13% MOX fuel (fig. 5, left). This percentage has been chosen in order to keep the European plutonium stock more or less constant, to serve as a resource for future fast reactors.

As a representative HTR, the Chinese HTR-PM design has been selected (fig. 5, right) as most near-term option, as it is under construction at the time of writing of this document. This reactor design uses pebble fuel with 8.1% enriched coated particles.

Fig. 5. Left: EPR plant; right: HTR plant.

In the current model, all enriched UOx pellet fuels are reprocessed, and MOX, HTR and PHWR fuel is not (except for the alternative case with HTR with plutonium fuelling, see chap. 3).

3.2 World case

The reference world scenario in this study is taken from the scenarios studied by IIASA – WEC. Despite IIASA – WEC studies are based on some data established in late 1990, they are chosen because of the availability of their data until the end of the 21st century. The chosen IIASA – WEC scenario for this study is labeled « C2 », it is described as « Ecologically driven, Renewables and new nuclear », and is based on a moderate growth of energy needs in the world:

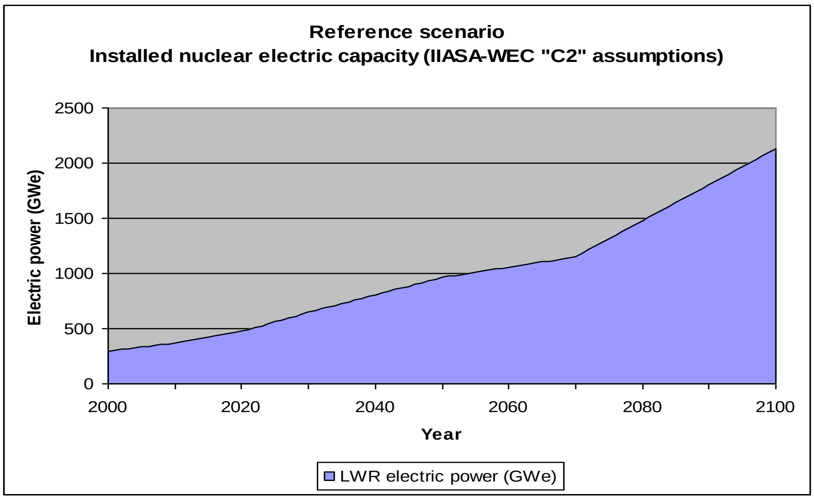


Fig. 6: World case – Nuclear electric capacity

More recent studies about world energy forecasts have been since then published, such as the IAEA study « Energy, Electricity and Nuclear Power Estimates for the Period up to 2030 » (Ref. [IAEA, 2006]), but their data seldom consider the post-2035 period. We can even so compare on the common period of time [2000-2035] the installed nuclear electricity capacities between the different energy forecasts, in order to make more reliable our reference scenario choice:

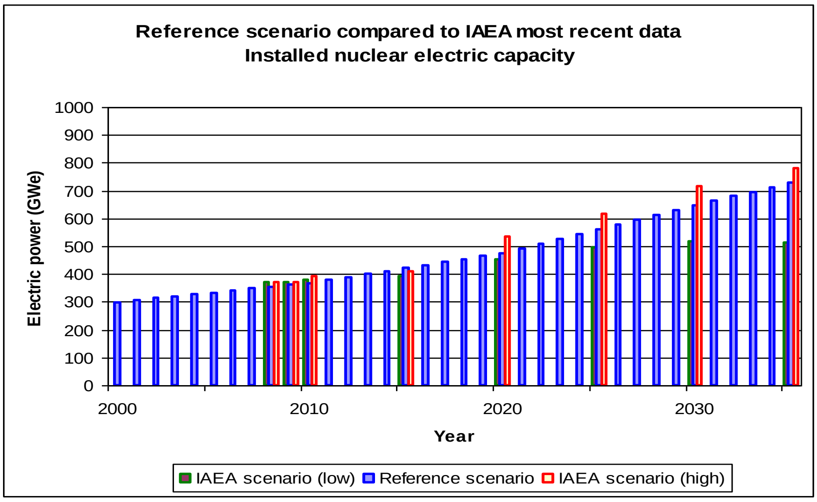


Fig. 7: World case – Comparison of nuclear electric capacities

For the assessment of the world reference scenario and its variations, the COSAC code ("Code de Scenario pour l'Aval du Cycle") that has been developed by AREVA for the twelve past years, was used in this study to simulate the flows of fissile material, fresh fuel, spent fuel, high level waste as well as all intermediate stocks and fuel cycle facility throughput.

The COSAC code is a scenario based computer model for the simulation of the fuel cycle. It models the installations where the nuclear material is stored, irradiated or handled, such as: mines, manufacturing facilities, reactors, cooling pools, intermediate and ultimate storage facilities, reprocessing facilities, etc. It can compute the nuclear parameters such as mass inventory, isotopic proportion, decay heat and radiotoxicity in each installation of the fuel cycle

The COSAC code uses a simplified approach to compute material isotopic evolutions within each installation, as well as material flows between the installations. This simplified approach results in a good compromising balance between accuracy of the results and computational speed, for open, partially closed or fully closed fuel cycle studies.

The simplified calculations carried out by COSAC are solutions to matrix equations. These matrices are buit up on the nuclear parameters to be followed during the fuel cycle: in-flux depletion of the fuel loaded the reactor, radioactive decay of the spent fuel after its discharge from the reactor, decay heat and radiotoxicity release of nuclear material for ages of time. Matrices are implemented in COSAC as input data, they are not part of the coded software.

In addition to the assumption of global installed nuclear electricity capacity associated to the chosen reference scenario for the world context, we assume a fraction of this electricity capacity is provided by MOX fuel. This fraction is comprised between 11% and 13.5%, as shown on the below graph, because it allows a quite well-balanced plutonium flow in the LWR fleet between the UOx spent fuel reprocessing and the MOX fresh fuel manufacturing:

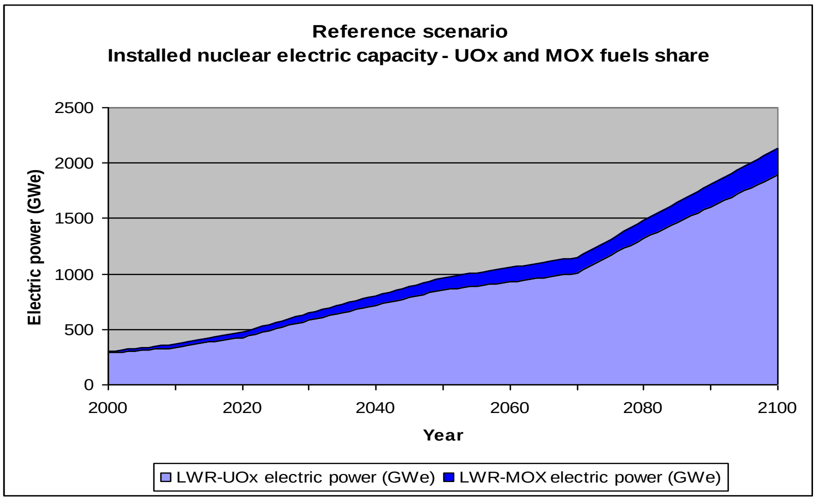


Fig. 8: World case – UOx and MOX share on nuclear electricity capacity

Included this MOX percentage in the LWR fleet, the average ratio of resource consumption by the reference scenario is thus **19.8 tons of natural uranium consumed by LWR per TW_{elec}.h delivered by LWR (**19.8 t/TW_{elec}.h).

About minor actinide production, their average ratio for the reference scenario is **6.10 kg of minor actinides produced by LWR per TW_{elec}.h delivered by LWR** (6.10 kg/TW_{elec}.h).

Note:
We nevertheless insist whatever the chosen reference scenario is for the world context, and even if this choice may appear as open to criticism especially with regard to the forecasts about energy needs at the end of the century, this study is a sensitivity study so that the incidence of the choice of a reference scenario is second rate with respect to the sensitivity results. Indeed all the results of the world study are expressed as incremental values in comparison with the reference scenario values.

4. VARIATION SCENARIOS AROUND THE REFERENCE CASES

4.1 European reference case with alternative fuels

In order to find out to what extent the use of alternative HTR fuels may alleviate the demand for nuclear resources, the effects of thorium and plutonium fuel are analysed.

Thorium is a heavy metal like uranium, and it consists for 100% from the isotope Th-232. It is not fissile, like U-235, but fertile like U-238. After capture of neutron, the Th-232 nucleus will convert into a U-233 nucleus. U-233 is very well fissionable, like U-235. Therefore thorium fuel will always be a mixture of thorium with a fissionable material, in our case 20% enriched uranium. For optimal thorium use, an enrichment as high as possible is needed, and 20% is the highest acceptable for proliferation reasons.

Plutonium can be used very well as a fuel in HTRs. However, as in this study we follow a policy of preserving enough plutonium for future fast reactors, only second generation plutonium is used for HTRs. First generation plutonium is plutonium retrieved from reprocessing spent uranium oxide fuel, and it is used as MOX in LWR or preserved for future use in fast reactors. Second generation plutonium is plutonium retrieved from reprocessing spent MOX fuel. It is still fissile for 42%. It could be used in HTRs in case the fast reactors ill not become available.

4.2 World reference case with alternative fuels and alternative rhythms of HTR deployment

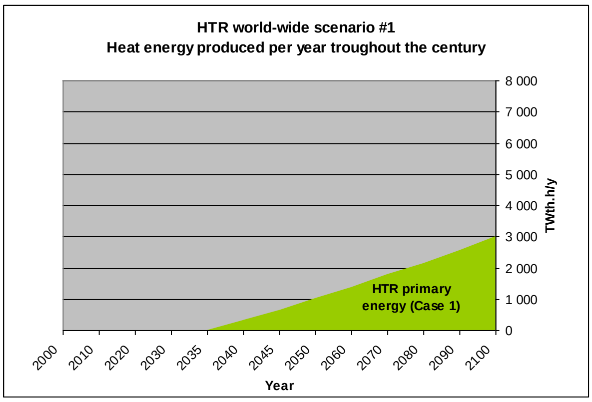
<u>World reference case with aternative rhythms of HTR deployment</u>
Four HTR deployment scenarios have been studied on the basis of the reference scenario, each of them can be distinguished by the amount of heat delivered by HTR in 2100, and by the rhythm the heat is delivered by HTR throughout the 21^{st} century.

Scenarios 1 & 2 consider a heat production by HTR of 3000 TW_{heat}.h in 2100.
Scenarios 3 & 4 consider a heat production by HTR of 5000 TW_{heat}.h in 2100.

These values of heat production by HTR are chosen in compliance with the sensitivity goal of this study and which consists in the assessment of the impact of deploying HTR on natural resources. In order to fix some orders of magnitude, these values of heat production in 2100 can be compared with those coming from the IIASA – WEC scenario chosen as the reference scenario.

Thus, accordingly to the IIASA – WEC assumptions, scenarios 1 & 2 represent 4.1% of the world primary energy in 2100, whereas scenarios 3 & 4 represent 6.9% of the world primary energy at the same year.

The rhythms throughout the century of the heat production by HTR for the four selected scenarios are shown on the below graphs:



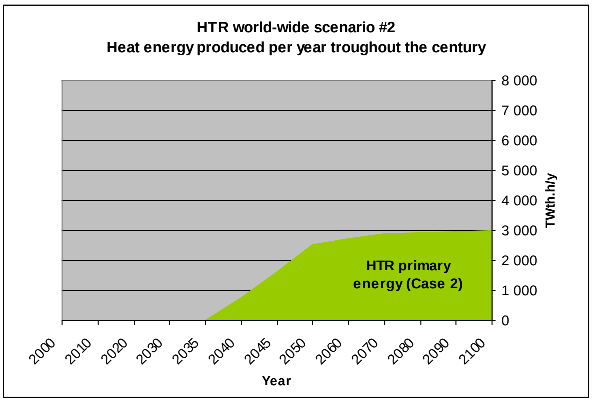


Fig. 9a: World case –HTR deployment for Case #1

Fig. 9b: World case – HTR deployment for Case #2

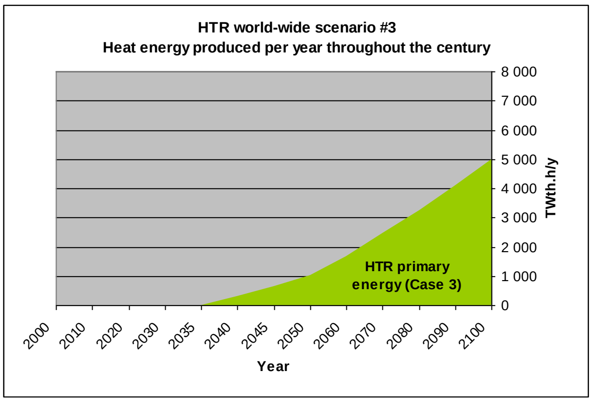


Fig. 9c: World case –HTR deployment for Case #3

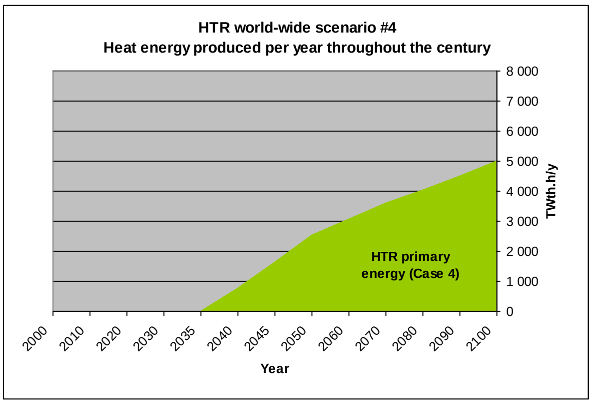


Fig. 9d: World case – HTR deployment for Case #4

One can notice on these graphs all HTR deployments are assumed to start in 2035. According to these various rhythms of HTR deployments, the cumulated amounts of heat delivered by HTR for the period of time [2035-2100] are:

- for scenario 1: of 108 000 TW_{heat}.h,
- for scenario 2: of 168 000 TW_{heat}.h,
- for scenario 3: of 152 000 TW_{heat}.h,
- for scenario 4: of 213 000 TW_{heat}.h.

We insist on the remark these rhythms of HTR deployments are chosen in compliance with the aim of conducting a sensitivity study. In any case they do not express a forecast of what nuclear energy, especially HTR energy, would be or should be during the 21st century.

In order to fix some orders of magnitude, the cumulated amounts of heat delivered by HTR for the period of time [2035-2100] can be compared with those coming from the IIASA – WEC scenario chosen as the reference scenario.

Thus, accordingly to the IIASA – WEC assumptions, the cumulated amounts of heat delivered by HTR for the period of time [2035-2100] represent:
- for scenario 1: 2.6% of the world primary energy needs on the same period of time,
- for scenario 2: 4.2% of the world primary energy needs on the same period of time,
- for scenario 3: 3.9% of the world primary energy needs on the same period of time,
- for scenario 4: 5.4% of the world primary energy needs on the same period of time.

A final assumption is made about electricity delivered by HTR in cogeneration: this is indeed assumed to replace some conventional means of electricity production, such as coal plants or gas turbines, so that the several considered HTR deployments never act on the installed nuclear electricity production presented in par. 3.2 as the reference scenario.

World reference case with alternative HTR fuel types

The several rhythms of HTR deployments presented in the previous paragraph are studied by considering several types of fuels loaded in the HTR cores:

- UOx-fuelled HTR: this fuel is the basic fuel for the study. The Cases #1, 2, 3 & 4 presented in the previous paragraph are considering UOx-fuelled HTR only. Uranium contained in uranium oxide is assumed to be enriched at 4.2% in U-235. It is enriched from natural uranium (mine). The tails exiting the enrichment plant are assumed to contain 0.25% in U-235.

- Pu-fuelled HTR: this fuel is an alternative fuel for HTR, especially studied in the case Fast Neutron Reactors (FNR) would arrive late for the 21st century and plutonium. It is studied in the so-called Case #1bis. This case is based on exactly the same HTR deployment as Case 1 presented in the previous paragraph but some of the deployed HTR are Pu-fuelled HTR instead of being UOx-fuelled HTR. Plutonium is coming from MOX spent fuel reprocessing. This plutonium is called 2nd generation-plutonium. To meet the scenario requirements in terms of HTR deployment, some UOx-fuelled HTR have to be added to Pu-fuelled HTR so that Case #1bis is presenting both UOx- and Pu-fuelled HTR. The proportions of each are given on the below graph, they respectively reach the value of about 40% and 60% at the end the century:

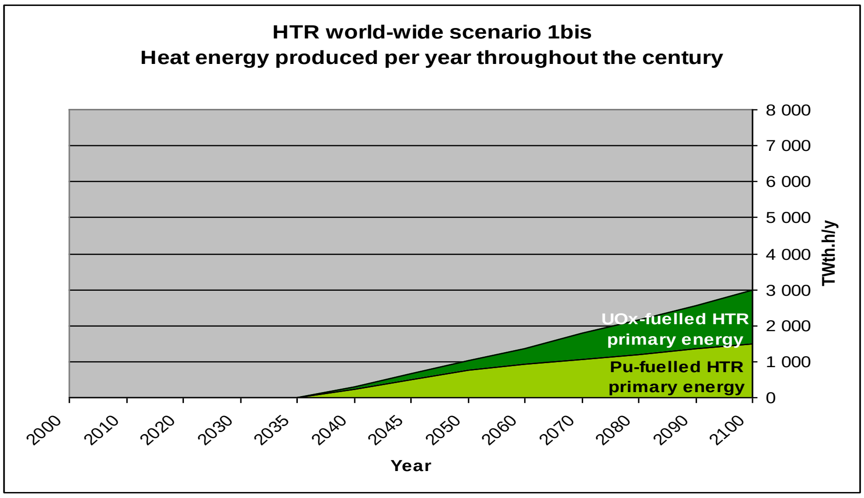


Fig. 10: World case –HTR deployement for Case #1bis

- U/Th fuelled HTR: this fuel is considered as an alternative to plutonium use in HTR. However, this choice implies FNR are no longer expected for the 21st century at least. It is studied in the so-called Case #1ter. This case is based on the same HTR deployment as the Case 1 presented in the previous paragraph. Uranium / thorium fuel is made of 40%-uranium and 60%-thorium (cf. table 1 in par. 2.2). Thorium irradiation in the core leads to the conversion of some Th-232 nuclides into U-233 nuclides. These in-core created U-233 nuclides are liable to fission, as well as U-235, so they can reduce the total amount of uranium that is needed to be loaded in the HTR cores.

As previously announced, the results of this study are expressed in comparison with the reference scenario described in par. 3.2. So the impact of each case of HTR deployments on the natural resources is given in terms of extra masses of natural resources required by the considered HTR case with respect to the equivalent case without any HTR deployment that means the chosen reference scenario.

5. DETAILED RESULTS

5.1 Detailed results about European reference case with alternative fuels

5.1.1 European reference case with UOx-fuelled HTR

<u>**Reactor capacities and uranium consumption**</u>

In fig. 11, the reactor capacity evolution for the 21st century is depicted. In brown, orange and red, the existing European reactor park consisting of the five 'average' reactor types as defined in par. 3.1.3 can be seen. No lifetime extension is assumed here. In blue, the new Generation III LWR park with constant capacity is shown. The slightly lowered capacity level with respect to the current nuclear park is caused by the higher efficiency of the GenIII reactors, serving the same electricity demand with a lower capacity.
The non-electrical demand is met by HTR reactors, reflecting the demand structure described in par. 3.1.2.

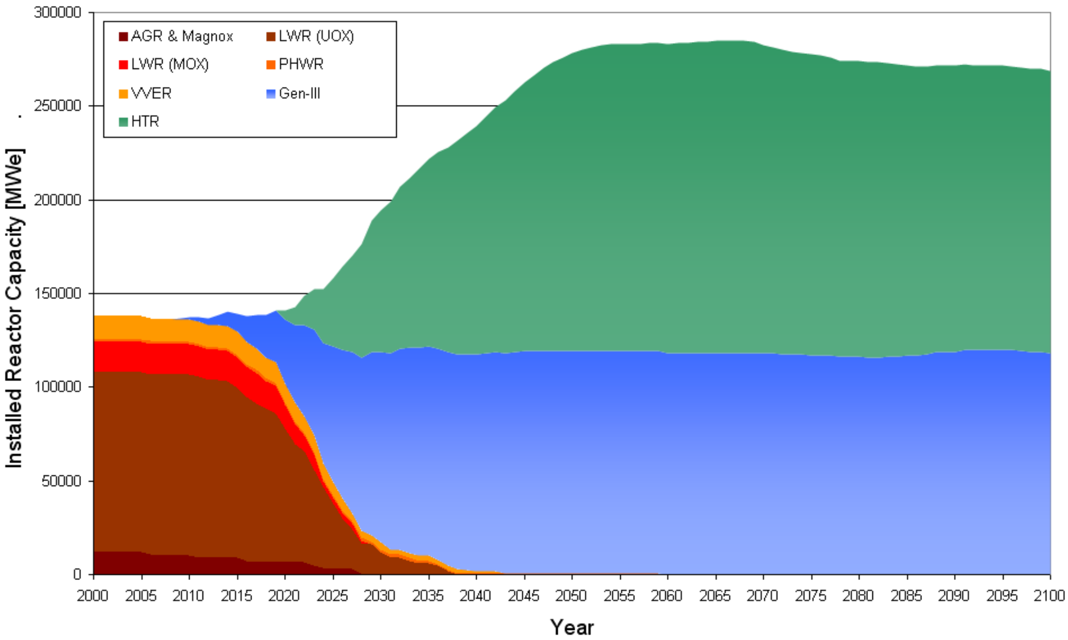


Fig. 11. Reactor capacity evolution for the existing and future European reactor park.

In fig. 12, the available stocks of natural uranium, reprocessed uranium and plutonium are shown. The initial uranium resources for Europe are assumed to be 30% of those indicated in the 'Red Book' of the OECD Nuclear Energy Agency [OECD/NEA, 2009]. The initial stocks of reprocessed uranium and plutonium are based on [OECD/NEA, 2007] and on [OECD/NEA, 2008].
The plutonium stock stays at a constant level throughout the century, in order to save sufficient plutonium for future fast reactors.
The uranium stock decreases, but natural uranium resources will be sufficient for the needs of the century. The reprocessed uranium stock can be seen as additional, although less attractive than natural uranium, because of its U-232 content, that has a high radiation intensity. Additionally, the enrichment has to be slightly increased, to compensate for the U-236 content.
The part of natural uranium that is consumed by HTR is 1 234 000 tons for the 21st century; this leads to an average specific ratio of natural uranium consumption by HTR of about 12.9 tons/TW_{heat}.h.
This total consumption of natural uranium by HTR over the 21st century represents about 20% of the conventional identified resources, as indicated in [OECD/NEA, 2009], and about 9% of the total resources in the earth's crust, including the not yet discovered resources (see chap. 2).

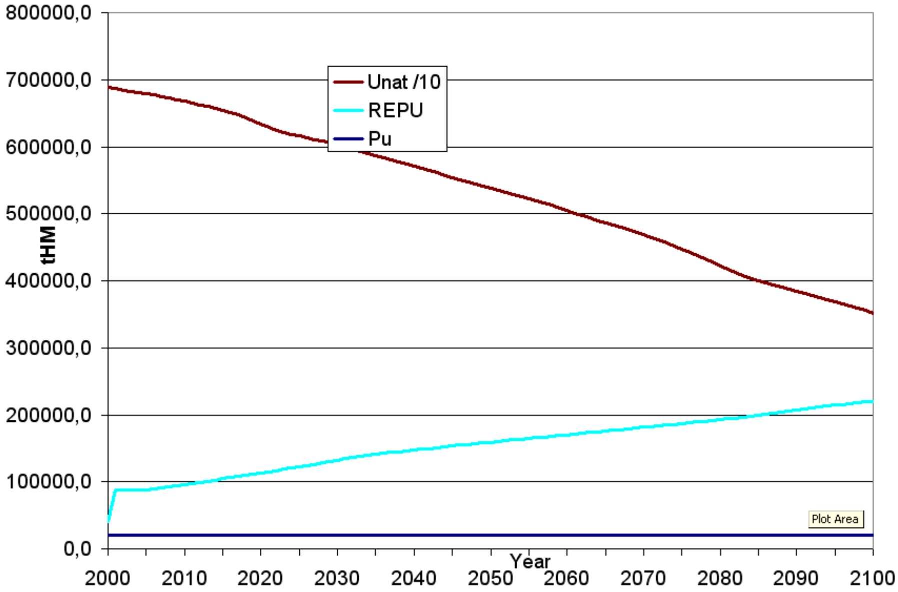


Fig. 12. Evolution of reserves of natural uranium, reprocess uranium and plutonium. The natural uranium reserves are divided by 10 to make them fit the graph.

Nuclear waste production

After minimally two years of storage in the reactor's spent fuel basin, the spent fuel is transported to either a reprocessing plant or an interim spent fuel storage facility. Here the spent fuel is stored during the period that it is still producing significant amounts of heat through radioactive decay. The high level waste arising from the reprocessing plant is transported to this interim storage facility as well.

In fig. 13, the evolution over the century of the amounts of spent fuel, both reprocessed and unreprocessed, is shown. It is split up in LWR, HTR and spent MOX for use in fast reactors. The LWR comprises both existing Generation II and new Generation III reactors. The spent MOX is kept out of the normal LWR waste stream, as it is not to be seen as waste to be entering the final waste repository, but as a resource to be processed into new nuclear fuel at a later stage. The unit is ton heavy metal, so only the weight of the spent fuel itself is being shown here. The associated storage volumes will differ, as for the HTR fuel also the graphite fuel element will be disposed of.

Based on existing interim storage practice, a reasonable facility size of 3000 tHM was derived [Roelofs, 2011]. This would result in about 23 of such facilities throughout Europe in the year 2100.

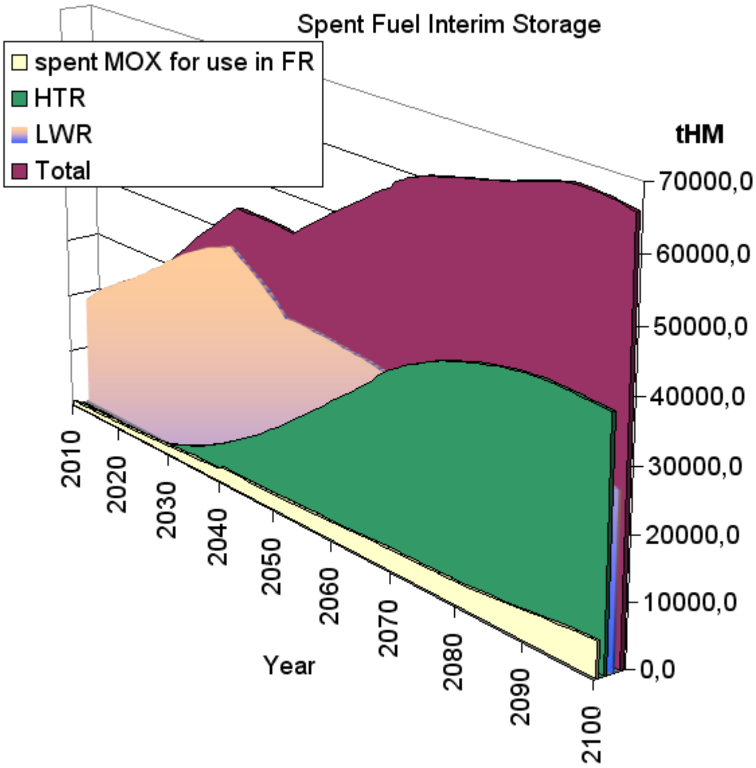


Fig. 13. Interim storage required capacities.

After a minimum of 40 years of interim storage, the waste is transferred to a final repository. Fig. 14 shows the amounts of waste to be stored here for the period to the year 2150, split up in LWR and HTR waste. Based on American and Finnish practice, a capacity of 10000 tHM can be seen as reasonable [Roelofs, 2011]. This would result in about 8 such facilities throughout Europe in the year 2100.

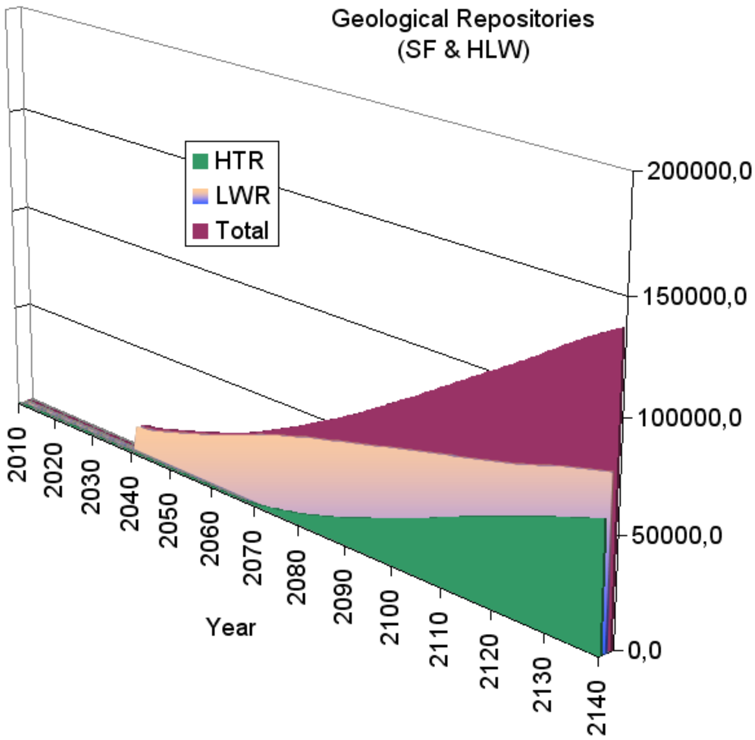


Fig. 14: Final storage required capacities.

5.1.2 European reference case with U/Th-fuelled HTR

Fig. 15 shows the resource use of HTRs during the 21st century in the scenario considered. With the Th fuel considered, a uranium resource conservation of about 20% for the HTR fuel would be achieved. For the uranium consumption of the total European nuclear park, including the LWR, it would earn a conservation of 8% (fig. 16).

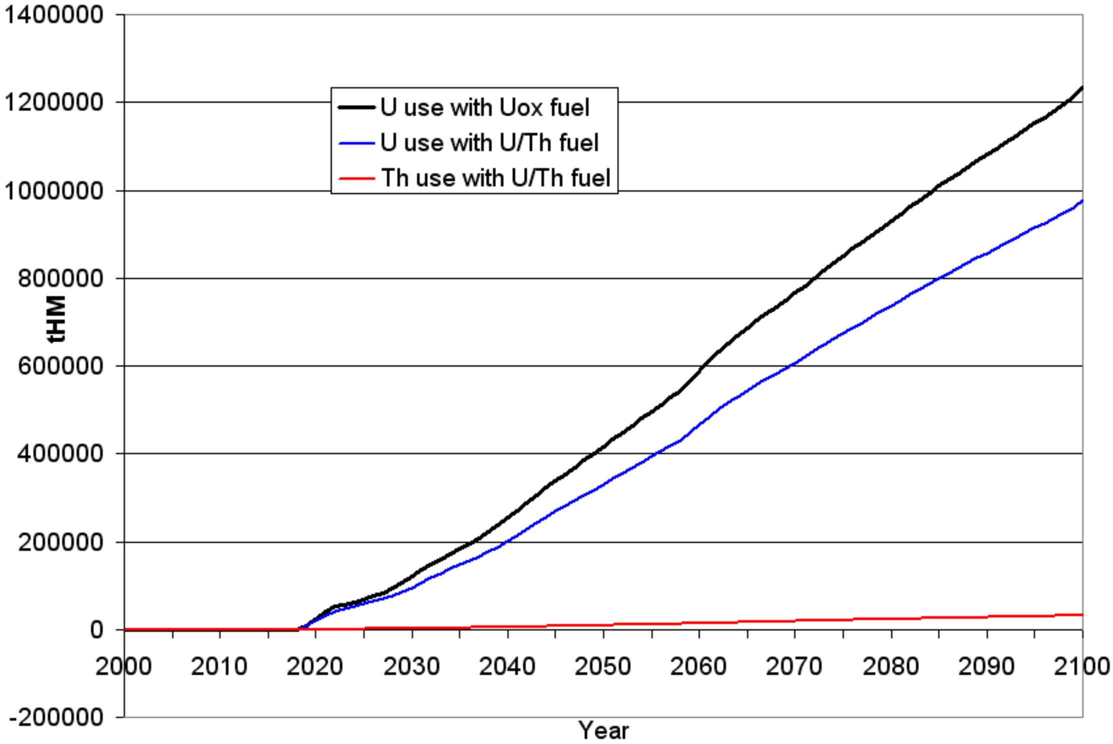


Fig. 15: Resource use for uranium and thorium fuel (non-electric only)

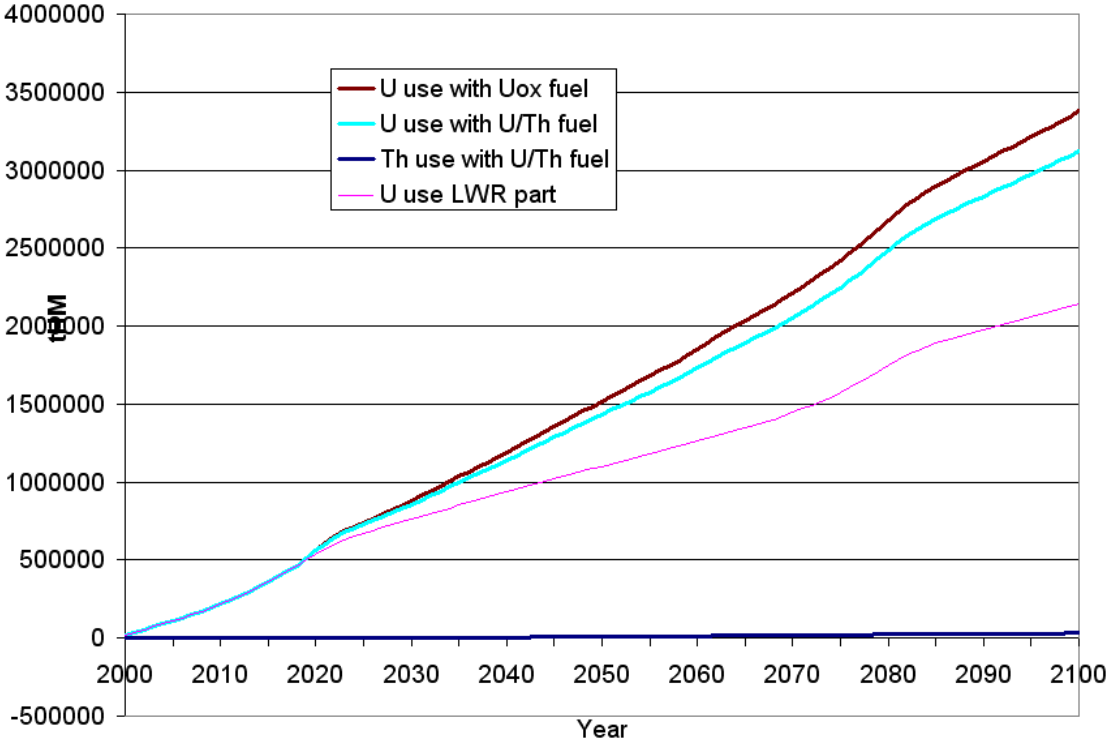


Fig. 16: Resource use for uranium and thorium fuel (total nuclear park)

During the 21st century, 314 tHM of plutonium will become available from MOX reprocessing in the current scenario. When distributing this over the HTR park during the 21st century, it can cover 2.5% of the HTR fuel demand. The other 97.5% would be covered by uranium fuel. In practice however, the available plutonium would be distributed just over a few reactors, covering a larger percentage of their fuel use.

5.2 Detailed results about world reference case with alternative rhythms of HTR deployment and alternative HTR fuel types

5.2.1 Case 1 – World reference case with UOx-fuelled HTR

This scenario case is considering UOx-fuelled HTR. These are deployed from 2035 to 2100 and they provide 3000 MW_{heat}.h in 2100.

On the same period of time [2035-2100], the cumulated amount of heat delivered by all the HTR reaches the value of 108 000 TW_{heat}.h.

Uranium consumption

The evolution of the extra consumption of natural uranium required by such a deployment of HTR is shown on fig. 17:

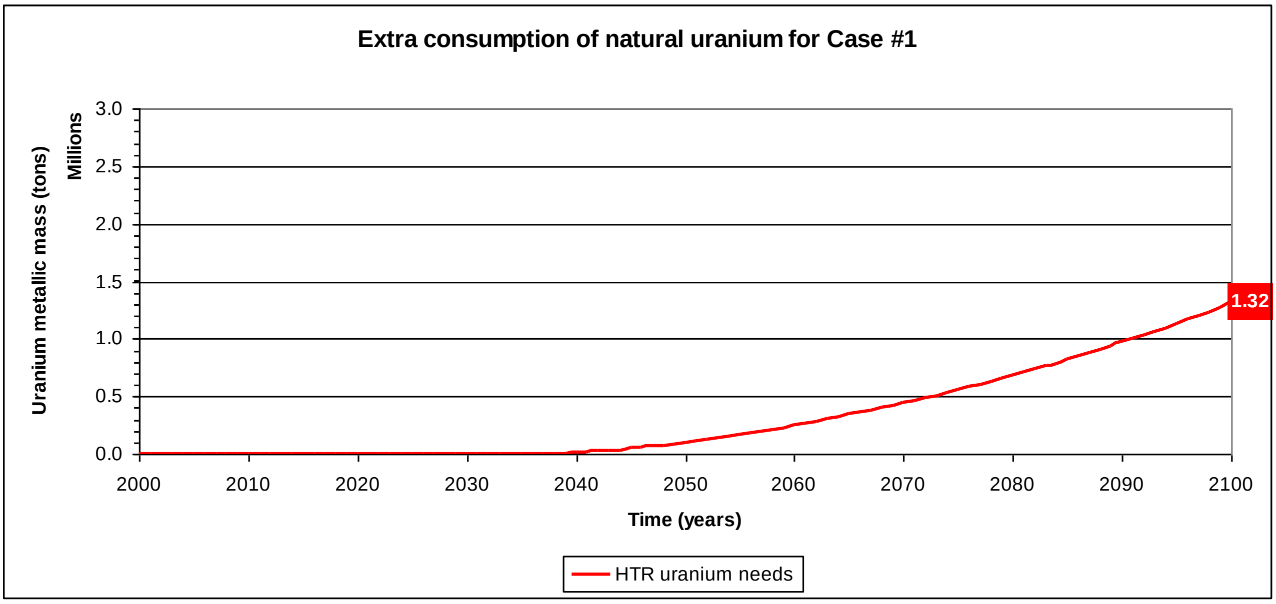


Fig. 17: World case #1 – Extra uranium consumption

The extra consumption of natural uranium reaches the value of 1 320 000 tons in 2100. This value has to be placed in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 108 000 TW_{heat}.h. This leads to an average resource consumption from HTR of 1 320 000 / 108 000, i.e. about **12.2 tons of natural uranium consumed by HTR per TW_{heat}.h delivered by HTR**.

Nuclear waste production

The evolution of the extra production of minor actinides induced by such a deployment of HTR is shown on Fig. 18:

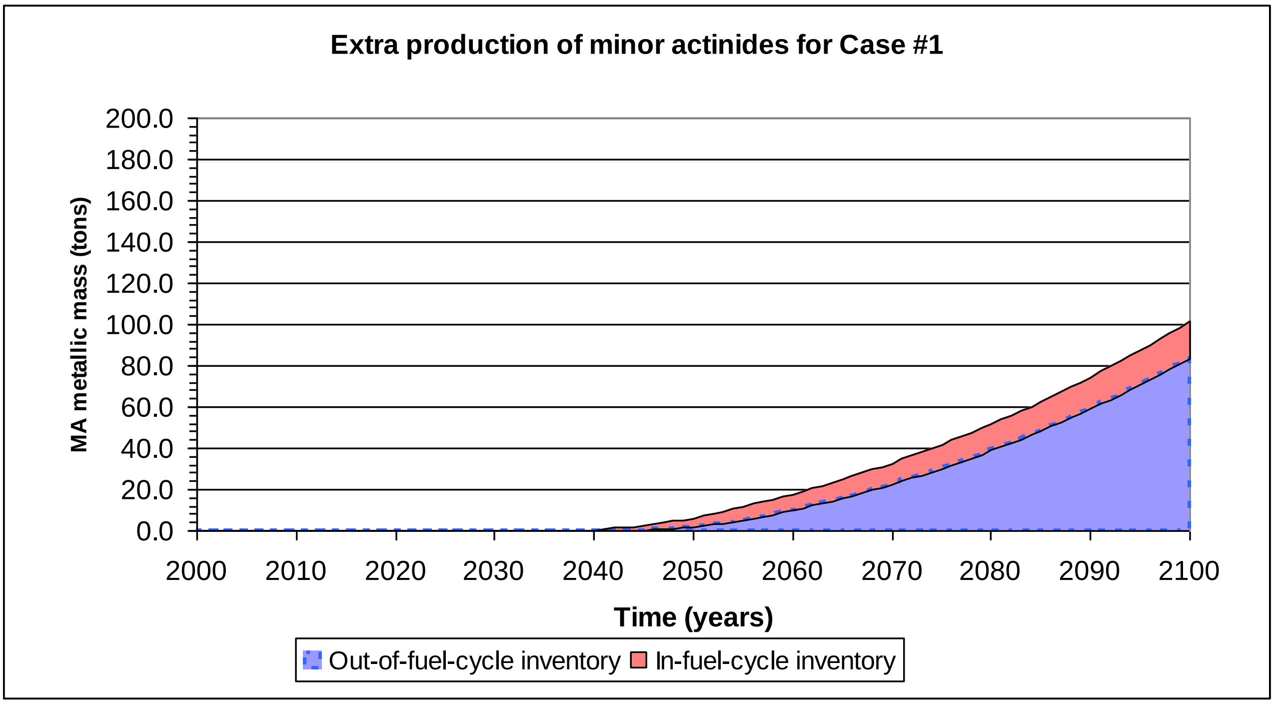
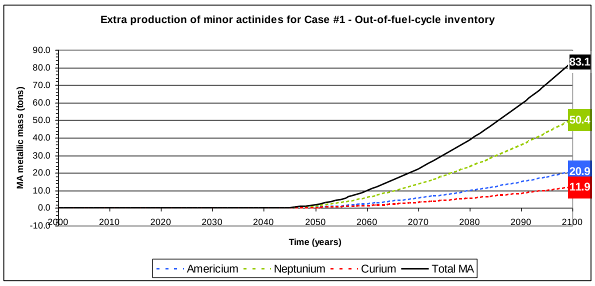


Fig. 18: World case #1 – Extra nuclear waste production

The extra production of minor actinides reaches the global value of 101 tons in 2100. This global value has tot be put in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 108 000 TW_{heat}.h. This leads to an average minor actinide production from HTR of 101 / 108 000, i.e. about **0.935 kg of minor actinides produced by HTR per TW_{heat}.h delivered by HTR**.

As shown on the two next graphs (Fig. 19a & 19b), the global value of 101 tons reached in 2100 can be split up in 83 tons of minor actinides located out of the fuel cycle (i.e. unused spent fuel after discharge from the reactors and/or ultimate waste after reprocessing operations) and 18 tons of minor actinides located in the fuel cycle (i.e. fuel being burned in the reactors and/or spent fuel stored in the decay pools before reprocessing):



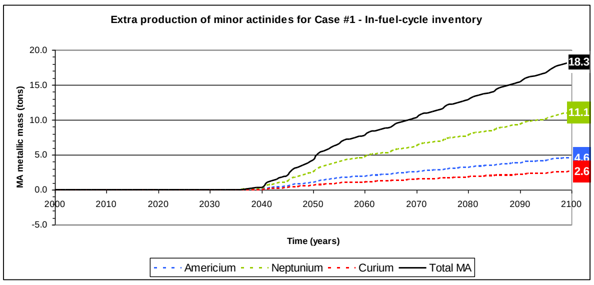


Fig. 19a: World case #1 – Out-of-fuel-cycle waste inventory **Fig. 19b: World case #1 – In-fuel-cycle waste inventory**

5.2.2 Case 1bis – World reference case with Pu-fuelled HTR

This scenario case is considering some Pu-fuelled HTR and some UOx-fuelled HTR. Both Pu-fuelled HTR and UOx-fuelled HTR are deployed from 2035 to 2100, and they globally provide 3000 MW_{heat}.h in 2100.

On the same period of time, the cumulated amount of heat delivered by all the HTR reaches the value of 108 000 TW_{heat}.h. About 60% of this amount are delivered by Pu-fulled HTR, and 40% by UOx-fuelled HTR.

Uranium consumption

The evolution of the extra consumption of natural uranium required by such a deployment of HTR is shown on Fig. 20:

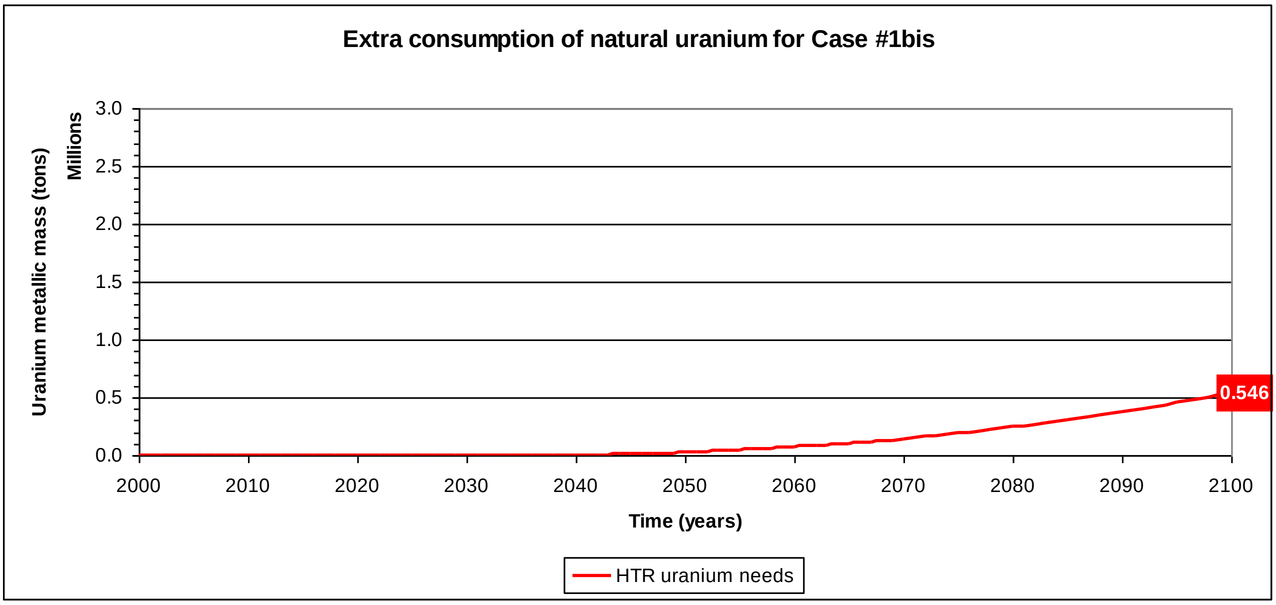


Fig. 20: World case #1bis –Extra uranium consumption

The extra consumption of natural uranium reaches the global value of 546 000 tons in 2100. This global value has to be placed in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 108 000 TW_{heat}.h. This leads to an average ratio of resource consumption by HTR of 546 000 / 108 000 = **5.06 tons of natural uranium consumed per TW_{heat}.h delivered by HTR**.

So uranium consumption is much reduced by using plutonium instead of uranium in part of the HTR fleet. In comparison with the results obtained for the UOx-fuelled HTR scenario previously studied in the Case #1, one can notice the reduction of uranium consumption is roughly achieved in the same proportion as the part Pu-fulled HTR represent in the total HTR fleet, that means about 60% (see par. 4.2).

Minor actinide production

The evolution of the extra production of minor actinides induced by such a deployment of HTR is shown on Fig. 21:

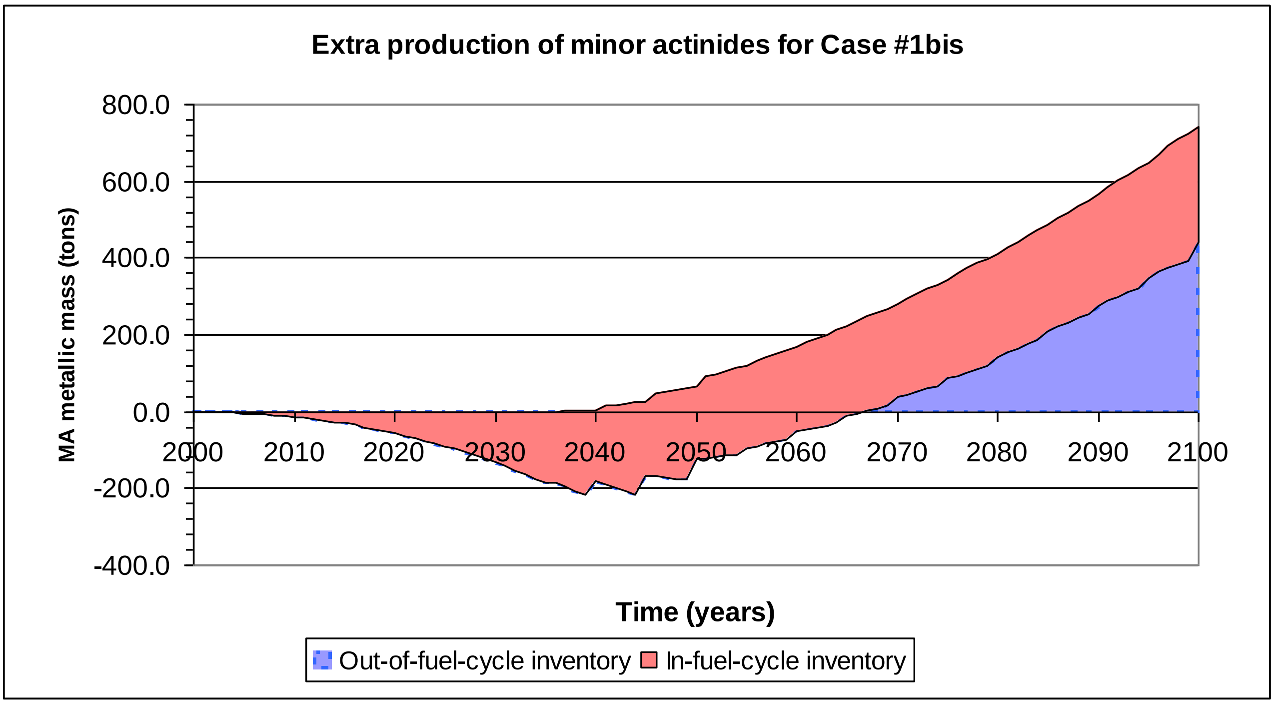


Fig. 21: World case #1bis – Extra nuclear waste production

The extra production of minor actinides reaches the global value of 744 tons in 2100. This global value has tot be put in front of the total amount of heat delivered by HTR for the period of time [2035-2100], that is 108 000 TW_{heat}.h. This leads to an average ratio of minor actinide production by HTR of 744 / 108 000 = about **6.89 kg of minor actinides produced by HTR per TW_{heat}.h delivered by HTR**.

As shown on the two next graphs (Fig. 22a & 22b), the global value of 744 tons reached in 2100 can be split up in 443 tons of minor actinides located out of the fuel cycle (i.e. unused spent fuel after discharge from the reactors and/or ultimate waste after reprocessing operations) and 301 tons of minor actinides located in the fuel cycle (i.e. fuel being burned in the reactors and/or spent fuel stored in the decay pools before reprocessing):

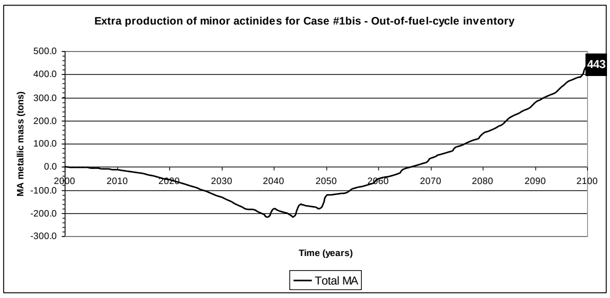


Fig. 22a: World case #1bis – Out-of-fuel-cycle waste inventory

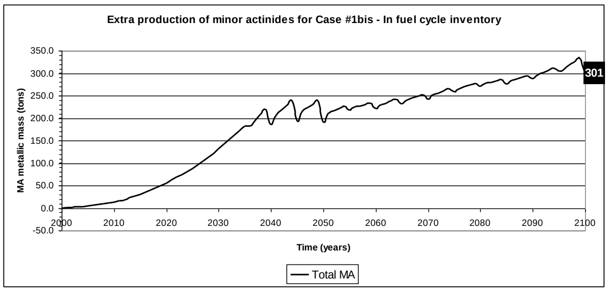


Fig. 22b: World case #1bis – In-fuel-cycle waste inventory

For the first period of the scenario, before HTR deployement (<2035), one can observe on the two above graphs a relative decrease of the extra minor actinide production out of the fuel cycle, as well as a relative increase of the extra minor actinide production in the fuel cycle. This can be explained by the strategy used in the present Case #1bis, which consists in recycling the 2nd-generation of Pu in the HTR instead of considering spent LWR-MOX fuel as an unused spent fuel. So, the spent LWR-MOX fuel is staying in the fuel cycle instead of being left out of the fuel cycle, as it is left out in the reference scenario and in the previously studied Case #1. As a consequence the balance of these two decreased and increased minor actinide productions, both out of and in the fuel cycle, is null for the whole first period (< 2035) of the scenario.

For the second period of the scenario, after HTR deployment has begun (>2035), one can observe on the two above graphs a straight increase of the extra minor actinide productions both out of and in the fuel cycle: this can be explained as the result of plutonium irradiation, instead of uranium irradiation, in part of the HTR fleet. Indeed, due to high capture cross sections of plutonium in epithermal neutron spectrum that is found in HTR cores, plutonium irradiation in HTR produces more minor actinides than if uranium was irradiated for an equivalent amount of delivered energy.

So that, at the end of the scenario (2100), the total extra minor actinide production is globally much increased (744 tons), comparared to the results obtained for the full uranium-fuelled HTR scenario studied in the previous Case #1bis (101 tons).

5.2.3 Case 1ter – World reference case with U/Th-fuelled HTR

This scenario case is considering U/Th-fuelled HTR. These are deployed from 2035 to 2100 and they provide 3000 MW_{heat}.h in 2100.

On the same period of time [2035-2100], the cumulated amount of heat delivered by all the HTR reaches the value of 108 000 TW_{heat}.h.

Uranium consumption

The evolution of the extra consumption of natural uranium required by such a deployment of HTR is shown on Fig. 23:

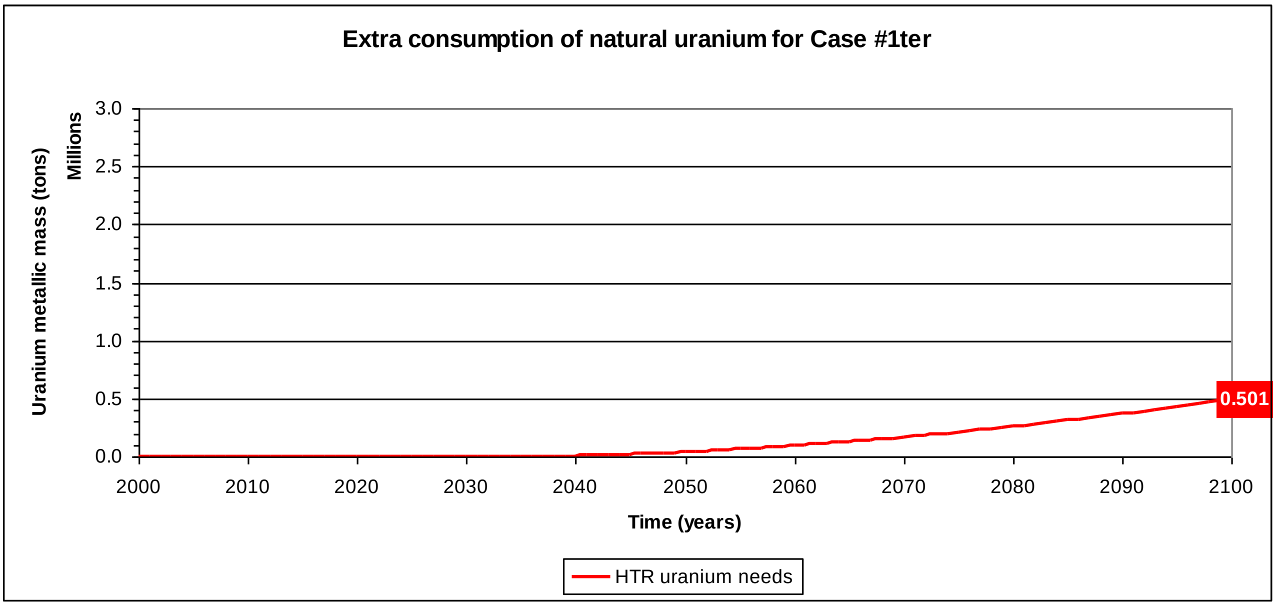


Fig. 23: World case #1ter –Extra uranium consumption

The extra mass of natural uranium reaches the global value of 501 000 tons in 2100. This global value has to be placed in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 108 000 TW_{heat}.h. This leads to an average ratio of resource consumption by HTR of 501 000 / 108 000 = **4.64 tons of natural uranium consumed per TW_{heat}.h delivered by HTR**.

So uranium consumption is much reduced by using thorium, in addition to uranium, in the HTR fuel. Indeed, thorium irradiation in HTR produces some fissile material (i.e. U233) that is then fissioned in the place of U235 in the HTR core. The amount of U235 that must be loaded in HTR to provide a given amount of energy is so reduced. The reduction of uranium consumption that is achieved by this blended U/Th-fuel is roughly in the same proportion as thorium is taking place of uranium in the HTR fuel, that means about 60% (see par. 2.2), compared with the results obtained for the full uranium-fuelled HTR scenario studied in the previous Case #1.

Thorium consumption

As Case 1ter scenario is the only scenario in this study where U/Th fuel is used to feed HTR cores, the present paragraph is dedicated to thorium consumption.

The evolution of thorium consumption for Case 1ter scenario is shown on Fig. 24:

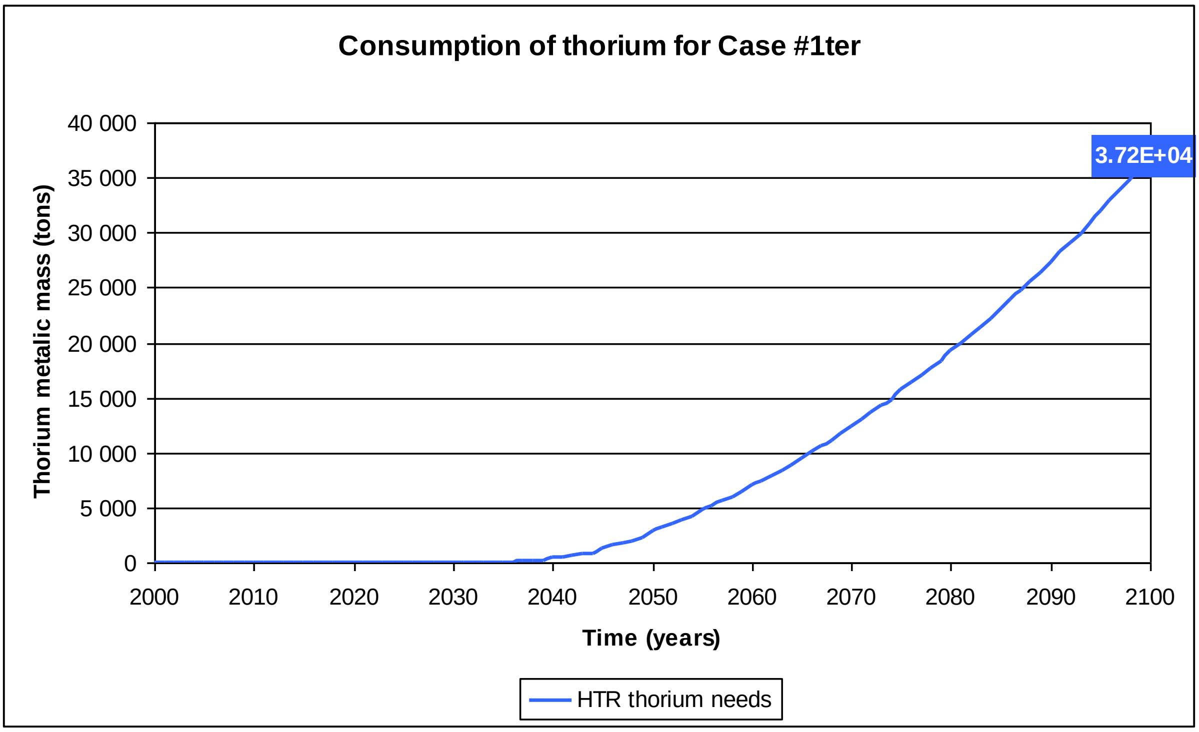


Fig. 24: World case #1ter – Thorium consumption

The total mass of thorium consumed for the Case #1ter reaches the value of 37 200 tons in 2100. This total value has to be placed in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 108 000 TW_{heat}.h. This leads to an average ratio of resource consumption by HTR of 37 200 / 108 000 = **344 kg of thorium consumed per TW_{heat}.h delivered by HTR**.

Nuclear waste production

The evolution of the extra production of minor actinides induced by such a deployment of HTR is shown on Fig. 25:

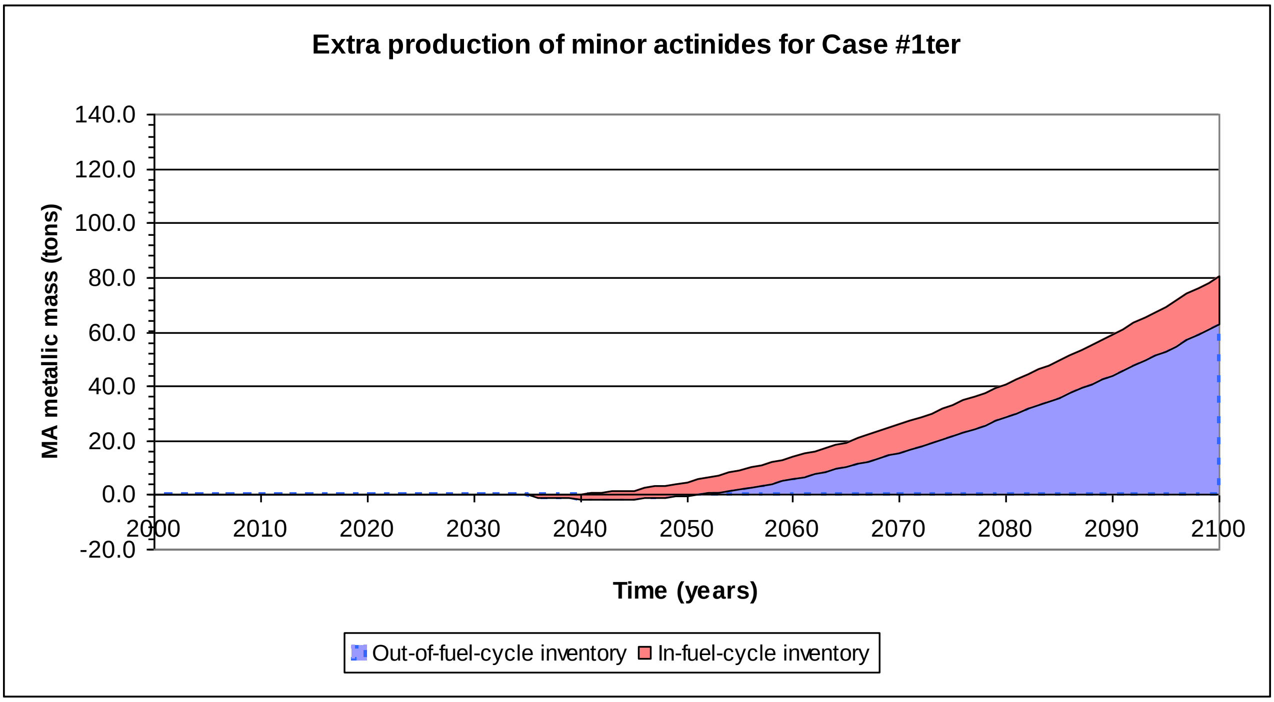


Fig. 25: World case #1ter – Extra nuclear waste production

The extra production of minor actinides reaches the global value of 81 tons in 2100. This global value has tot be put in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 108 000 TW_{heat}.h. This leads to an average ratio of minor actinide production by HTR of 81 / 108 0006 = **0.750 kg of minor actinides produced by HTR per TW_{heat}.h delivered by HTR**.

As shown on the two next graphs (Fig. 26a & 26b), the global value of 81 tons reached in 2100 can be split up in 63 tons of minor actinides located out of the fuel cycle (i.e. unused spent fuel after discharge from the reactors and/or ultimate waste after reprocessing operations) and 18 tons of minor actinides located in the fuel cycle (i.e. fuel being burned in the reactors and/or spent fuel stored in the decay pools before reprocessing):

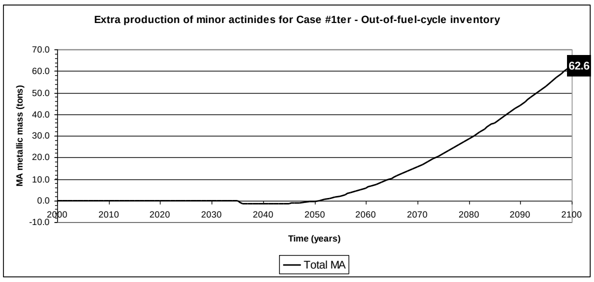


Fig. 26a: World case #1ter – Out-of-fuel-cycle waste inventory

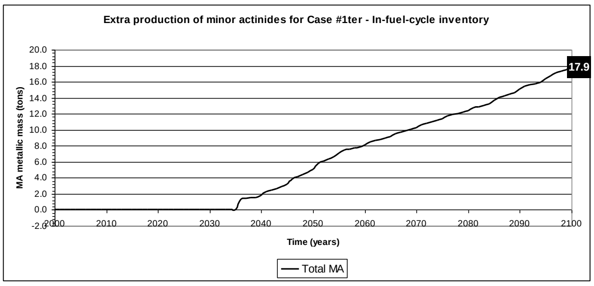


Fig. 26b: World case #1ter – In-fuel-cycle waste inventory

One can notice the quite little value (81 tons) of the extra production of minor actinides in this studied Case #1ter, compared with the results obtained for the Pu-fuelled HTR scenario (Case 1bis value: 744 tons) and even with the results obtained for the full uranium-fuelled HTR scenario (Case #1 value: 101 tons).

This can be explained by the location of thorium in Mendeleyev's periodic table, compared with uranium and plutonium locations: thorium is Z=90, that means two locations below uranium and four locations below plutonioum in Mendeleyev's periodic table. With regard to minor actinide production, thorium irradiation thus needs at least 5 radioactive β-decays and some neutron captures to produce some americium, instead of 3 radioactive β-decays if uranium is irradiated and only 1 radioactive β-decay if plutonium is irradiated (plus one or some neutron captures, too).

5.2.4 Case 2 – World reference case with UOx-fuelled HTR

This scenario case is considering U/Th-fuelled HTR. These are deployed from 2035 to 2100 and they provide 3000 MW_{heat}.h in 2100.

On the same period of time [2035-2100], the cumulated amount of heat delivered by all the HTR reaches the value of 168 000 TW_{heat}.h.

<u>**Uranium consumption**</u>

The evolution of the extra consumption of uranium required by such a deployment of HTR is shown on Fig. 27:

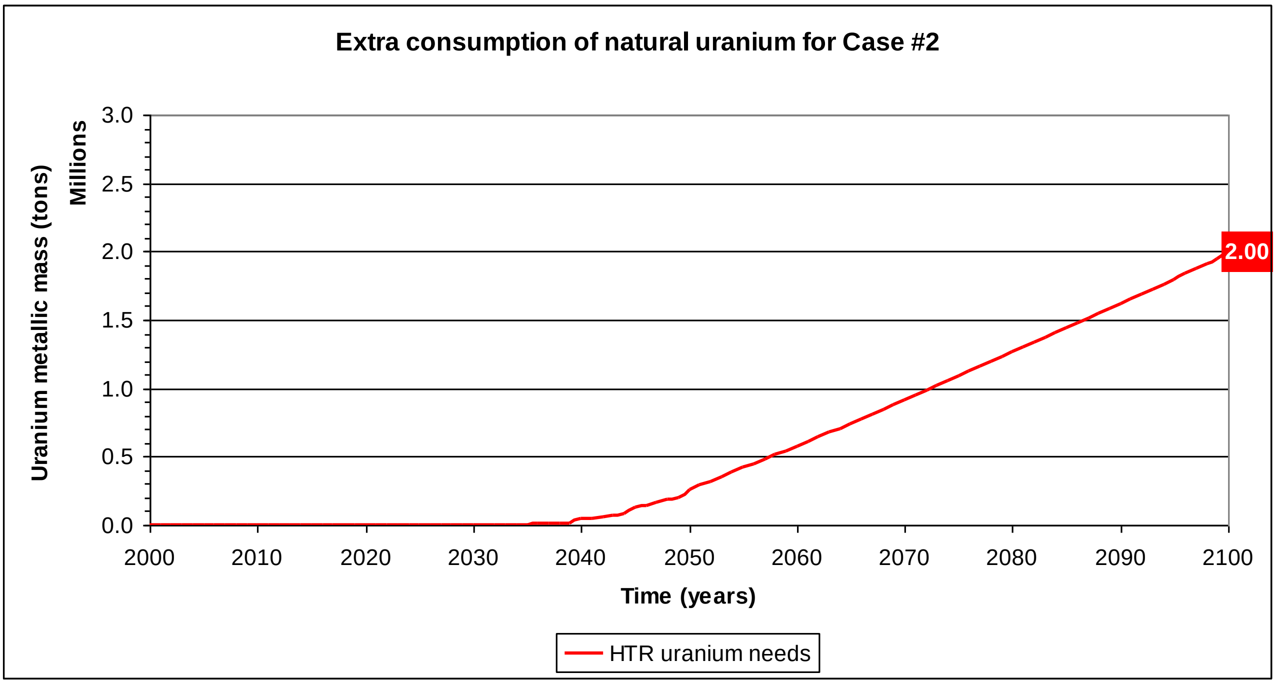


Fig. 27: World case #2 –Extra uranium consumption

The extra mass of natural uranium reaches the global value of 2 000 000 tons in 2100. This global value has to be placed in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 168 000 TW_{heat}.h. This leads to an average ratio of resource consumption by HTR of 2 000 000 / 168 000 = **11.9 tons of natural uranium consumed per TW_{heat}.h delivered by HTR**.

<u>**Nuclear waste production**</u>

The evolution of the extra production of minor actinides induced by such a deployment of HTR is shown on Fig. 28:

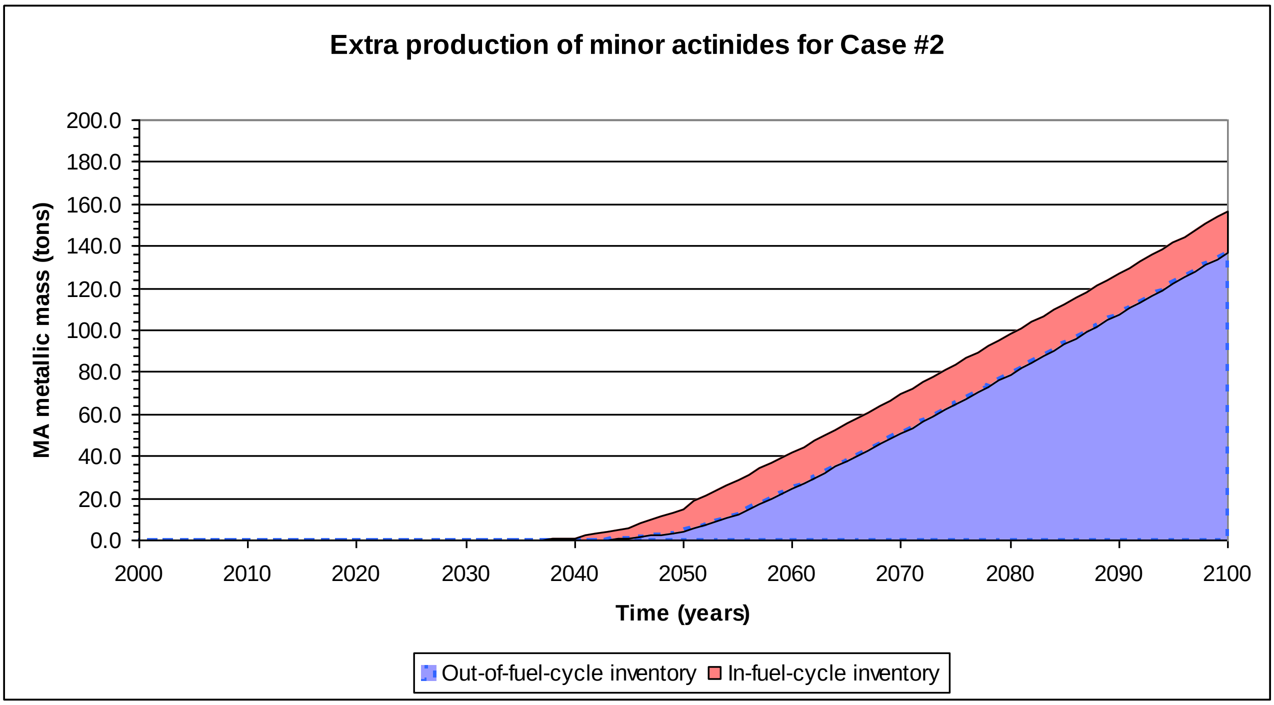
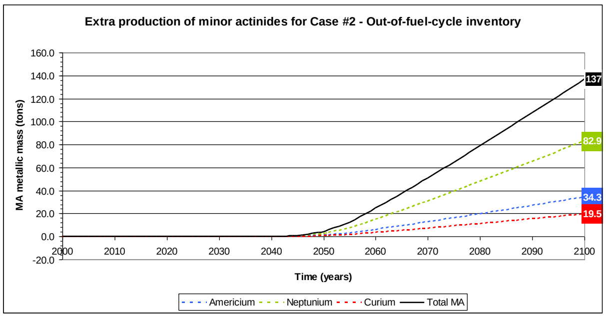


Fig. 28: World case #2 – Extra nuclear waste production

The extra production of minor actinides reaches the global value of 157 tons in 2100. This global value has tot be put in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 168 000 TW_{heat}.h. This leads to an average ratio of minor actinide production by HTR of 157 / 168 000 = **0.935 kg of minor actinides produced by HTR per TW_{heat}.h delivered by HTR**.

As shown on the two next graphs (Fig. 29a & 29b), the global value of 157 tons reached in 2100 can be split up in 137 tons of minor actinides located out of the fuel cycle (i.e. unused spent fuel after discharge from the reactors and/or ultimate waste after reprocessing operations) and 20 tons of minor actinides located in the fuel cycle (i.e. fuel being burned in the reactors and/or spent fuel stored in the decay pools before reprocessing):



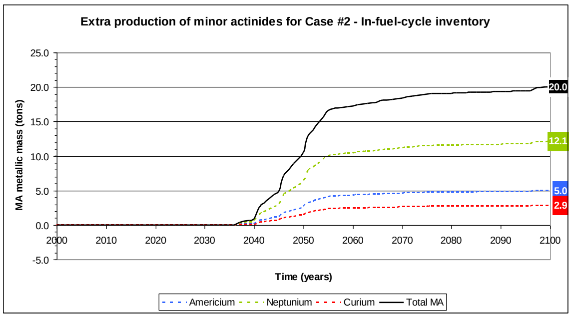


Fig. 29a: World case #2 – Out-of-fuel-cycle waste inventory **Fig. 29b: World case #2 – In-fuel-cycle waste inventory**

5.2.5 Case 3 – World reference case with UOx-fuelled HTR

This scenario case is considering U/Th-fuelled HTR. These are deployed from 2035 to 2100 and they provide 5000 MW_{heat}.h in 2100.

On the same period of time [2035-2100], the cumulated amount of heat delivered by all the HTR reaches the value of 152 000 TW_{heat}.h.

Uranium consumption

The evolution of the extra consumption of natural uranium required by such a deployment of HTR is shown on Fig. 30:

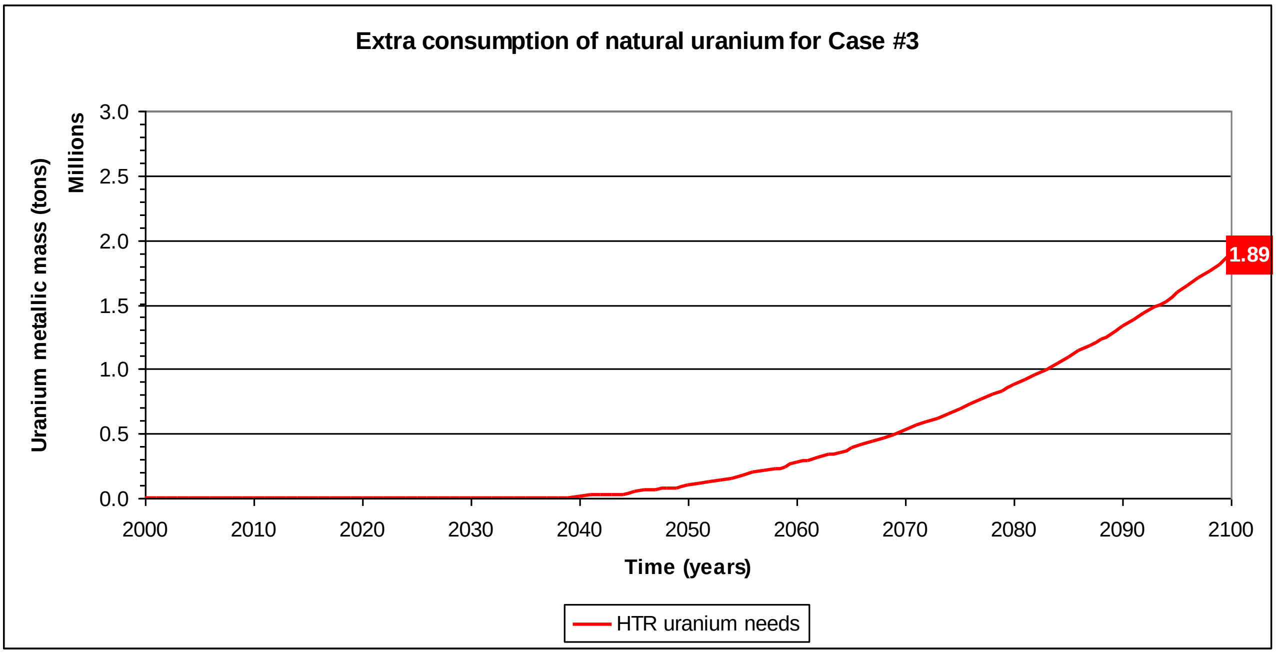


Fig. 30: World case #3 –Extra uranium consumption

The extra mass of natural uranium reaches the value of 1 890 000 tons in 2100. This value has to be placed in front of the total amount of heat delivered by HTR for the period of time [2035-2100], that is 152 000 TW_{heat}.h. This leads to an average ratio of resource consumption by HTR of 1 890 000 / 152 000 = **12.4 tons of natural uranium consumed by HTR per TW_{heat}.h delivered by HTR**.

Nuclear waste production

The evolution of the extra production of minor actinides induced by such a deployment of HTR is shown on Fig. 31:

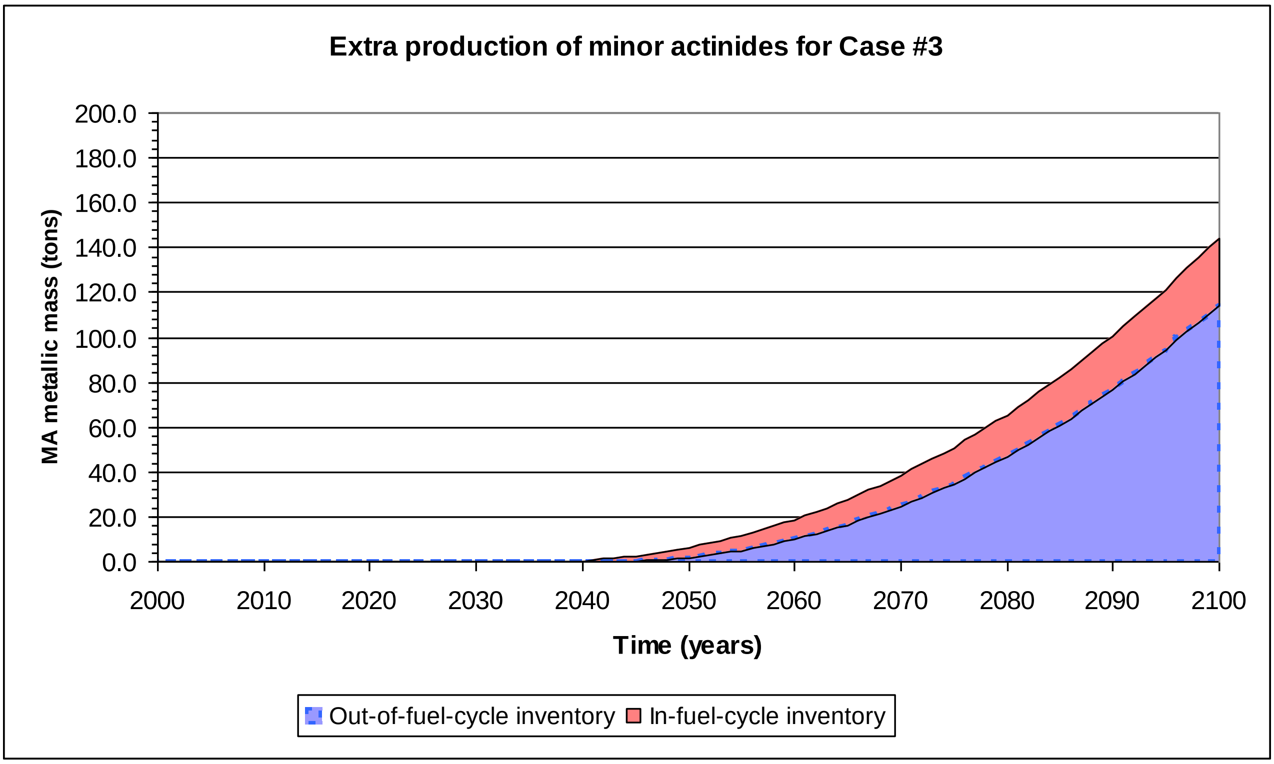


Fig. 31: World case #3 – Extra nuclear waste production

The extra production of minor actinides reaches the global value of 145 tons in 2100. This global value has tot be put in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 152 000 TW_{heat}.h. This leads to an average ratio of minor actinide production by HTR of 145 / 152 000 = **0.954 kg of minor actinides produced by HTR per TW_{heat}.h delivered by HTR**.

As shown on the two next graphs (Fig. 32a & 32b), the global value of 145 tons reached in 2100 can be split up in 115 tons of minor actinides located out of the fuel cycle (i.e. unused spent fuel after discharge from the reactors and/or ultimate waste after reprocessing operations) and 30 tons of minor actinides located in the fuel cycle (i.e. fuel being burned in the reactors and/or spent fuel stored in the decay pools before reprocessing):

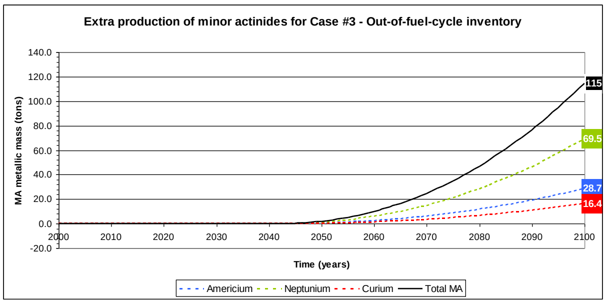


Fig. 32a: World case #3 – Out-of-fuel-cycle waste inventory

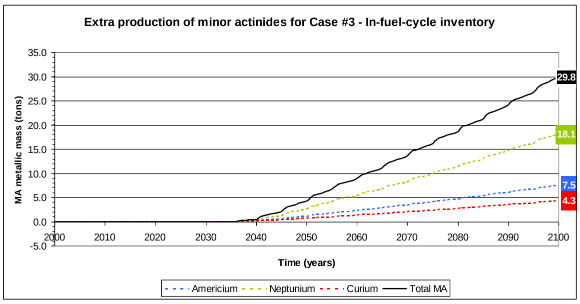


Fig. 32b: World case #3 – In-fuel-cycle waste inventory

5.2.6 Case 4 – World reference case with UOx-fuelled HTR

This scenario case is considering U/Th-fuelled HTR. These are deployed from 2035 to 2100 and they provide 5000 MW_{heat}.h in 2100.

On the same period of time [2035-2100], the cumulated amount of heat delivered by all the HTR reaches the value of 213 000 TW_{heat}.h.

Uranium consumption

The evolution of the extra consumption of natural uranium required by such a deployment of HTR is shown on Fig. 33:

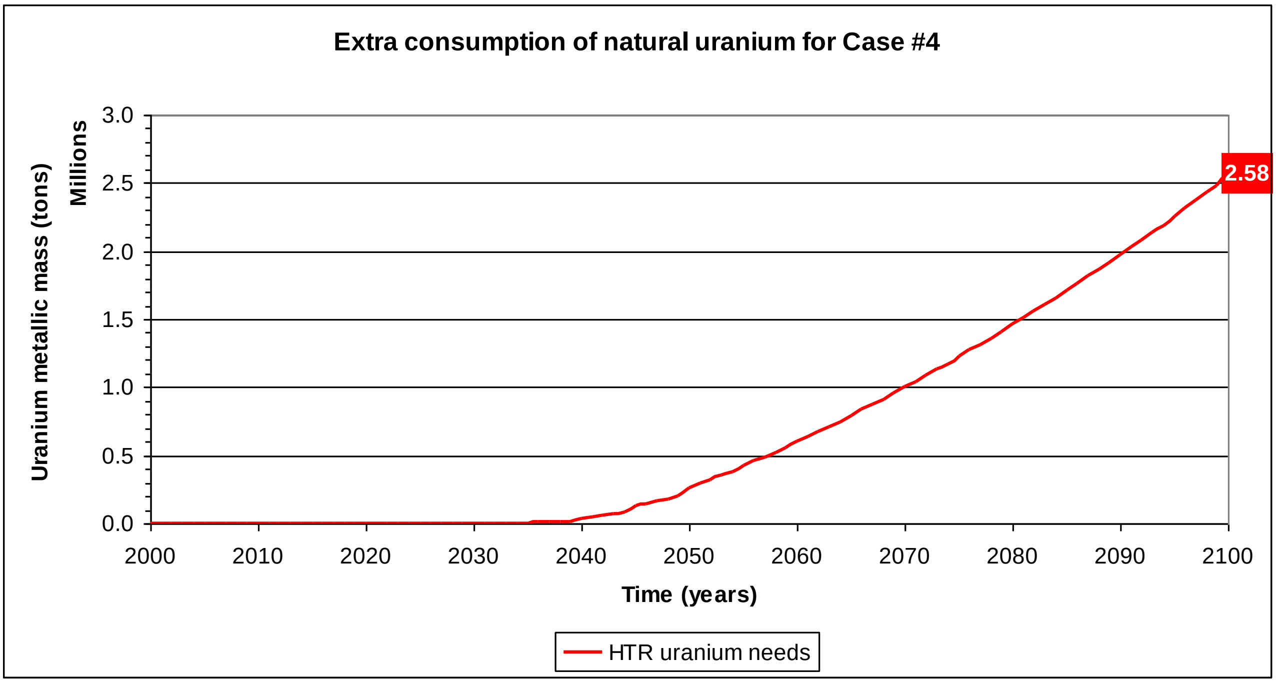


Fig. 33: World case #4 –Extra uranium consumption

The extra mass of natural uranium reaches the value of 2 580 000 tons in 2100. This value has to be placed in front of the total amount of heat delivered by HTR for the period of time [2035-2100], that is 213 000 TW_{heat}.h. This leads to an average ratio of resource consumption by HTR of 2 580 000 / 213 000 = **12.1 tons of natural uranium consumed by HTR per TW_{heat}.h delivered by HTR**.

Nuclear waste production

The evolution of the extra production of minor actinides induced by such a deployment of HTR is shown on Fig. 34:

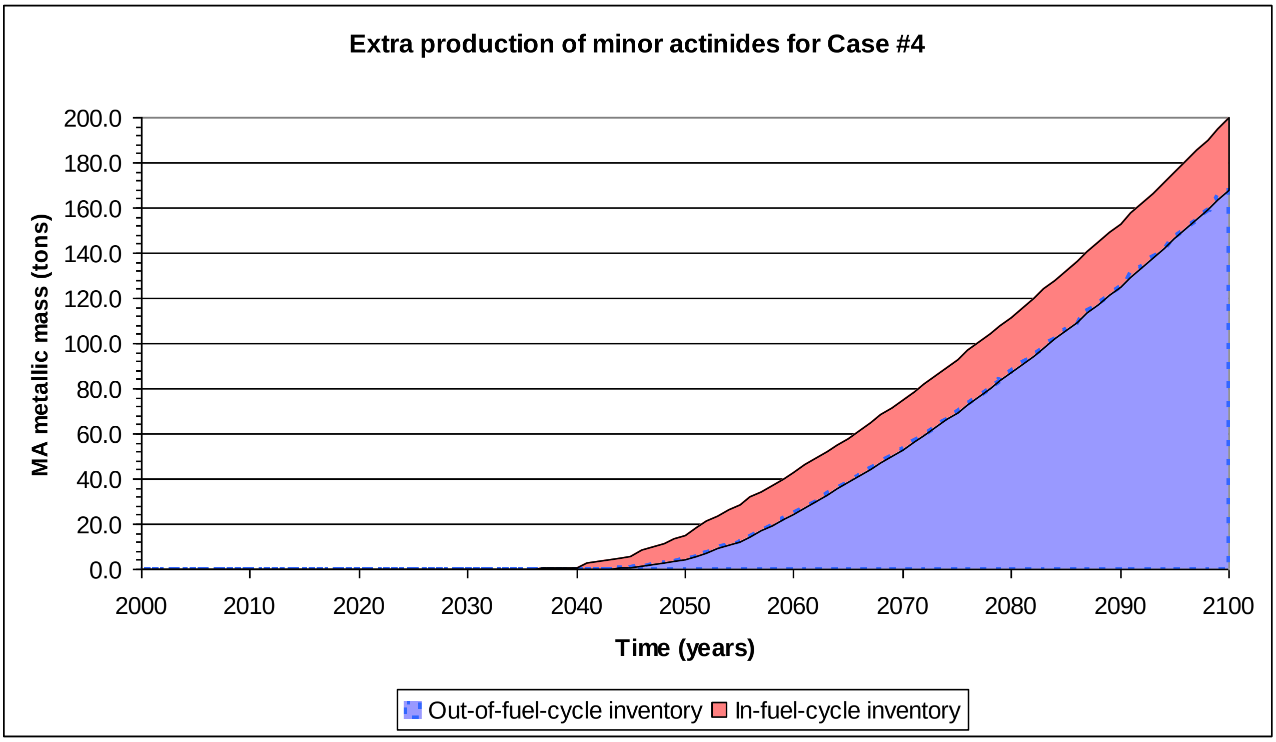


Fig. 34: World case #4 – Extra nuclear waste production

The extra production of minor actinides reaches the global value of 200 tons in 2100. This global value has tot be put in front of the amount of heat delivered by HTR for the period of time [2035-2100], that is 213 000 TW_{heat}.h. This leads to an average ratio of minor actinide production by HTR of 200 / 213 000 = **0.939 kg of minor actinides produced by HTR per TW_{heat}.h delivered by HTR**.

As shown on the two next graphs (Fig. 35a & 35b), the global value of 200 tons reached in 2100 can be split up in 168 tons located out of the fuel cycle (i.e. unused spent fuel after discharge from the reactors and/or ultimate waste after reprocessing operations) and 32 tons located in the fuel cycle (i.e. fuel being burned in the reactors and/or spent fuel stored in the decay pools before reprocessing):

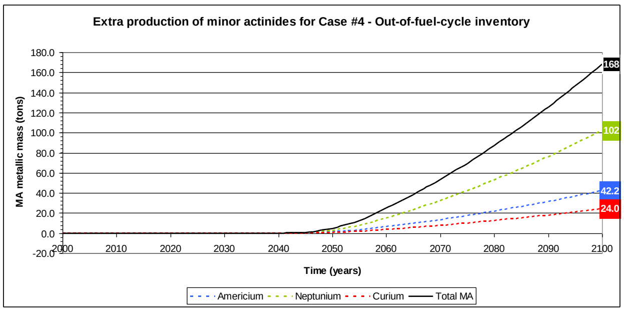


Fig. 35a: World case #4 – Out-of-fuel-cycle waste inventory

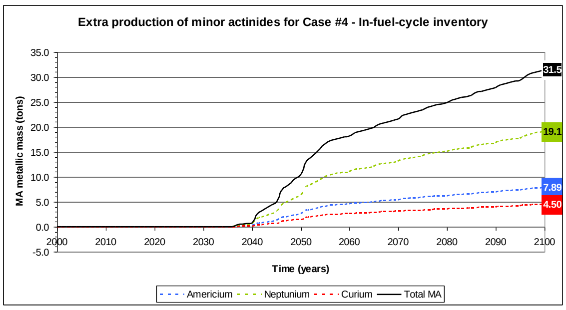


Fig. 35b: World case #4 – In-fuel-cycle waste inventory

6. SUMMARY OF THE RESULTS

6.1 Summary of the results obtained for the European study

6.1.1 Summary of the demand and capacity analysis

The European study was based on a demand scenario deemed realisitic by authoritative sources: SNE-TP for the electric demand, and IIASA/WEC for the non-electric demand. A nuclear heat demand has been derived based on this non-electric demand for the 21st century.
Based on the existing European nuclear park, the demand has been met in the model by replacing the current nuclear park by Gen III LWR (EPR in the model) and modular HTR for the non-electric nuclear heat demand (HTR-PM in the model).

6.1.2 Summary about the wast disposal analysis

The evolution over the century of the amounts of spent fuel, both reprocessed and unreprocessed, has been analysed, split up in LWR, HTR and spent MOX for use in fast reactors. Spent MOX is kept out of the normal LWR waste stream, as it is not to be seen as waste to be entering the final waste repository, but as a resource to be processed into new nuclear fuel at a later stage. Based on existing interim storage practice, 23 interim storage facilities and 8 final repositories would be needed throughout Europe in the year 2100.

6.1.3 Summary about resource analysis

The available stocks of natural uranium, reprocessed uranium and plutonium have been analysed, based on the 'Red Book' of the OECD Nuclear Energy Agency. Keeping the plutonium stock at a constant level throughout the century, in order to save sufficient plutonium for future fast reactors, the uranium stock decreases, however natural uranium resources will be sufficient for the needs of the century.
With Th fuel considered, a uranium resource conservation of about 20% for the HTR fuel would be achieved. For the uranium consumption of the total European nuclear park, including the LWR, it would earn a conservation of 8%.
Additional plutonium becoming available from MOX reprocessing during the 21st century, could cover 2.5% of the HTR fuel demand when distributed over the HTR park.

6.2 Summary of the results obtained for the world study

The world study is conducted as a sensitivity study based on a reference scenario. Each case of this sensitivity study (i.e. cases #1, 2, 3, 4, 1bis & 1ter) is associated to a specific HTR deployment and a specific HTR fuel type. All the studied cases consider HTR production (both heat and electricity) as replacing some conventional means of energy production such as coal, oil and gas.
As a consequence the results related to the world study are all expressed in terms of extra masses of natural resources that must be supplied to allow the various cases of considered HTR deployments.

6.2.1 Summary about natural uranium consumption

Cases #1, 2, 3 & 4, that consider only UOx-fuelled HTR, lead to the highest values of natural uranium consumption among all the studied cases, as indicated in the below table 2. The average ratio of uranium resource consumption by HTR per heat energy delivered is slightly greater than **12 tons/TW$_{heat}$.h**:

	Case 1	Case 2	Case 3	Case 4	Case 1bis	Case 1ter[1]
HTR heat energy in 2100 (TW_{heat}.h)	3000	3000	5000	5000	3000	3000
HTR cumulated heat energy (TW_{heat}.h)	108 000	168 000	152 000	213 000	108 000	108 000
Extra mass of nat.U (tons)	1 320 000	2 000 000	1 890 000	2 580 000	546 000	501 000
Ratio (t/TW_{heat}.h)	12.2	11.9	12.4	12.1	5.06	4.64

Table 2: World study – Summary of the uranium consumption results

This average ratio for UOx-fuelled HTR scenarios is however lower than the one calculated for the reference scenario (cf. par. 3.2), the displayed value of which was nearly 20 **tons/TW_{heat}.h**. Even if not expressed in exactly the same unit (per electricity energy delivered instead of per heat electricity energy delivered), this discrepancy can mainly be explained by the HTR features retained for this study (cf. table 1 in par. 2.2), especially the one related to efficiency.

Case #1bis, which scenario considers both UOx- and Pu-fuelled HTR for HTR deployment, considers the recycling of the 2nd generation-plutonium, i.e. the plutonium that is retrieved from the MOX spent fuel reprocessing. This plutonium is recycled in part of the HTR fleet, the other part being fed with UOx-fuelled HTR that remain still necessary to complete the HTR deployment. The proportions so achieved in 2100 are roughly 40% UOx-fuelled HTR and 60% Pu-fuelled HTR. Using 2nd generation-plutonium in place of uranium in 60% of the HTR fleet allows a reduction of about the same proportion of the induced impact on uranium resources by HTR deployment. This reduction of the impact is achieved while the MOX-fuelled part of the LWR fleet is fully maintained, i.e. approximatively 13% of the LWR fleet. Typically, the average ratio of natural uranium consumption by HTR per heat energy delivered is roughly reduced by a factor of 2 (**5.0 tons/TW_{heat}.h**) in comparison with the UOx-fuelled previously mentioned Cases #1, 2, 3 & 4.

Case #1ter only considers U/Th-fuelled HTR for the HTR deployment. This type of fuel is roughly made of 40%-uranium and 60%-thorium. Thorium is partially converted into fissionable uranium (U-233) during the irradiation of the fuel in the core. This in-core conversion allows a reduction of the impact induced by the HTR deployment on the uranium resources. Typically, the average ratio of natural uranium consumption by HTR per heat energy delivered is roughly reduced by a factor of 2 too (**4.7 tons/TW_{heat}.h**, value close to the Case #1bis value) in comparison with the UOx-fuelled previously mentioned Cases #1, 2, 3 & 4.

6.2.2 Summary about minor actinide production

The comparisons about minor actinide production by the various studied HTR scenarios are indicated in the below table 3. The U/Th-fuelled HTR case (**Case #1ter**) is showing the lowest minor actinide production, with an average ratio of minor actinide production per heat energy delivered of **0.750 kg/TW_{heat}.h**:

	Case 1	Case 2	Case 3	Case 4	Case 1bis	Case 1ter
HTR heat energy in 2100 (TW_{heat}.h)	3000	3000	5000	5000	3000	3000

[1] In addition to the 501 000 tons of natural uranium consumed by HTR in this scenario, Case 1ter also needs 37 200 tons of thorium. Rated to the total amount of heat energy delivered by HTR, this value leads to an average ratio of thorium consumption of 344 kg/TW_{heat}.h.

HTR cumulated heat energy (TW_{heat}.h)	100 254	167 136	139 458	201 671	102 186	103 084
Extra mass of MA (tons)	101	157	145	200	744	81
Ratio (kg/TW_{heat}.h)	0.935	0.935	0.954	0.939	6.89	0.750

Table 3: World study – Summary of the waste production results

The four studied UOx-fuelled HTR cases (i.e. **Cases #1, 2, 3 & 4**) are very close each other in terms of minor actinide production per heat energy delivered. Their average ratio is in the range of **[0.935-0.954] kg/TW_{heat}.h**. When compared with the LWR ratio (6.10 kg/TW_{elec}.h) of minor actinide produced per electricity energy released in the reference scenario (cf. par. 3.2), the UOx-fuelled HTR ratio of minor actinide production looks like quite low even if not expressed in exactly the same unit (per electricity energy delivered instead of per heat electricity energy delivered). This can be partly explained by the slightly more energetic neutron spectrum that exists in an HTR core (one can speak of an epithermal spectrum in an HTR core, instead of a thermal spectrum in a LWR core), which is more favourable for neutron absorption and destruction by fission of the minor actinides, and also partly explained by the HTR features retained for this study (cf. table 1 in par. 2.2), especially the one related to efficiency. The efficiency parameter indeed makes the minor actinide production ratio decrease by increasing the amount of energy released for a given amount of minor actinides produced.

The Pu-fuelled case (**Case 1ter**) shows the highest ratio of minor actinide production: **6.89 kg/TW_{heat}.h**. This can be explained by the location of the plutonium element in Mendeleyev's periodic table, which is 2-element upper located than uranium, and 4-element upper located than thorium.

7. CONCLUSIONS

7.1 Teachings from this study

This study aimed to estimate and compare several HTR deployment scenarios in terms of resource consumption and minor actinide production, either in Europe either in the whole world. It can teach us several things:

- First, about uranium resource consumption, the results obtained for the two families of studied scenarios (European ones and world ones) are very consistent. By considering the amount of natural uranium that is consumed by UOx-fuelled HTR to deliver an energy amount of 1 TWheat.h of industrial heat (what is called in this study “the average specific ratio of natural uranium consumption”), the two families of scenarios conclude on quite similar values, typically comprised between 12 and 13 tons/TW_{heat}.h.

  This range of values [12–13] of natural uranium tons/TW_{heat}.h approximatively leads to half a million tons of natural uranium would be consumed by HTR to let them provide about 40 000 TW_{heat}.h, if all the HTR are fuelled with UOx.

  This ratio between natural uranium mass and provided energy seems to be too high to let UOx-fuelled take a significant part of the energetic needs for this century. To fix the orders of magnitude of such energy needs, if one takes for granted the forecasts made by IIASA WEC in late 1990, 40 000 TW_{heat}.h would only represent about 1% of the world energy needs in industrial heat for the period [2035-2100] where HTR are assumed to be deployed in this study. On the other hand, according to the most recent « Red Book » published by OECD/NEA (Ref. [OECD/NEA, 2009]), half a million tons of natural uranium would represent represent 8% of the conventional identified resources, and about 4% of the total resources in the earth’s crust including the not yet discovered resources.

  Therefore, for the 21st century, UOx-fuelled HTR won’t compete with LWR in terms of uranium consumption as far as their deployment is limited to a “niche market”, that means a market made of quite specific industrial sites where heat is needed at a very intensive level and in a much concentrated place, such as Chemelot site.

  This conclusion is quite different if other fuel types than UOx are considered for feeding HTR cores, such as plutonium-fuel or uranium/thorium-fuel. Indeed, the present study indicates scenarios involving Pu-fuelled HTR or U/Th-fuelled HTR have their average specific ratio of natural uranium consumption reduced by a factor more than 2, reaching a value around 5 tons/TW_{heat}.h.

  As a consequence such scenarios involing Pu-fuelled HTR or U/Th-fuelled HTR could provide a significant amount of industrial heat for the 21st century, without jeopardizing uranium resources and LWR core feeding. So, with -fuelled HTR or U/Th-fuelled HTR, a significant fraction of 10% of the world energy needs in industrial heat could be supplied by HTR. Moreover, the present study doesn’t take into account the possible arrival of Fast Neutron Reactors (FNR) within the 21st century that would probably even more release the demand pressure on uranium resources.

- Second, about minor actinide production, all the presently studied scenarios lead to a quite low production of minor actindes in HTR. The average specific production of minor actinides by HTR is around 1 kg/TW_{heat}.h when UOx fuel is used. It is a bit less than 1 kg/TW_{heat}.h when U/Th fuel is used in HTR instead of UOx fuel. For the Pu-fuelled case, a higher value can be noticed, this case leading to an anverage specific production of minor actinides close to 7 kg/TW_{heat}.h. This can be explained by the location of the Pu-element in Mendeleyev's periodic table, as mentioned in par. 5.2.2.

More generally speaking, one must keep in mind all the present results are quite dependant on the assumptions made on the HTR features, especially the one related to the heat efficiency which is assumed to be 70% in this study (cf. table 1 in par. 2.2). This assumption means 70% of the fission energy delivered by HTR are assumed to be converted into industrial heat.

7.2 Outlook to further study

The presently studied cases #1bis and #1ter, that consider respectively Pu-fuel and U/Th-fuel types for HTR, could be followed by further studies. Indeed:

- the presently studied Pu-fuelled HTR case reveals 2nd generation-Pu can support only a limited HTR deployment because of the limited amount of available plutonium coming from the LWR spent fuel reprocessing. If one wants to go beyond this limit, some UOx-fuelled HTR must be added to the scenario in order to increase the HTR level and rhythm of deployment. Recycling 2nd generation Pu in HTR instead of 1st-generation was a choice made in order to maintain the LWR-MOX ratio to about 13% of the LWR fleet in the scenario, and to avoid the fission potential contained in this 2nd-generation Pu to decine by decaying. However questions can be raised about the incidence of using the 2nd generation-Pu in HTR on the date of a possible Fast Neutron Reactor (FNR) deployment in the century. Would using plutonium in HTR cores delay the FNR deployment, and in what extent? On the contrary, if FNR arrive sooner than expected during this century, would their breeding capacities help in the HTR deployment by providing some of the fissile materials that are required by the HTR deployment?

- The presently studied U/Th fuelled HTR case only considers once-through U/Th fuel in the HTR, that means U-233 is fissioned in the HTR as long as this nuclide is created by thorium conversion inside the HTR neutron spectrum. This scenario should be extended by a complete multi-recycling uranium-thorium fuel study. The in-core created U-233 fissile nuclide could so be retrieved from reprocessing, which could increase the amount of uranium saved in the fuel cycle, so that HTR fuel could be managed with no impact on the natural uranium resources.

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