ON THE ACCUMULATED PLUTONIUM MASS AGAINST THE BACKGROUND OF THE FIXED ELECTRICITY AMOUNT REGULATED BY LAW IN GERMANY

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Abstract

The Plutonium production in the German reactor park under the actual political guidelines is studied. The influence of different options (once-through scenario, single and double MOX recycling scenario) on the residual Plutonium masses are analysed and compared to a close to reality scenario. Additionally an insight into the consequences of a postulated lifetime extension on the residual Plutonium mass is given and the Plutonium reduction and the change of the Plutonium composition due to double recycling are demonstrated.

Introduction

The actual situation in Germany is characterized by a phase out scenario and the shut down of all reactors after a theoretical life period of 33 years regulated by law since 2003. Reprocessing is stopped by 2005 according to this law and the lifetime is fixed via the net amount of electricity (roughly 220 TWd) to be produced. The over all thermal energy produced can be calculated to 666 TWd gross in about 32 years [1], [2]. These strictly defined boundary conditions offer the possibility for a good estimation of the accumulated amounts of burnt fuel and the resulting amounts of Plutonium and minor actinides. The influence of the variation of different parameters on the residual Plutonium mass can be studied very well on this basis. The influence of different scenarios (once-through, idealized single and double Plutonium recycling and close to reality Plutonium recycling) on the residual Plutonium mass is studied.

Besides these scenarios the changes due to a postulated extension of the over all energy production up to 900 TWd thermal accordant to a 10 year lifetime extension will be analysed.

Cycle study

Used Calculation Methods

The calculations are preformed with the standard software KAPROS (KArlsruher PROgramm System) [3]. The special procedure KARBUS (KARlsruher BUrnup System) [4], see Fig. 1, is used. The flux and k_∞ calculations are performed using 69 energy group cell calculations for best estimate weighting function determination. The calculation is based on the methods of the cell code WIMS [5] and uses collision probability method. The cross sections are taken from a KAPROS master library based on ENDF/B-6.5. The calculated neutron fluxes are used for group collapsing to create the one group fluxes and cross sections needed for the burnup calculations in the module BURNUP which is based on KORIGEN [6]. The calculation scheme shown in Fig. 1 is stopped when the criticality limit k_∞=1.03 is reached [7]. Then the end of life burnup for the number of core burnup stagers (cycles) is then calculated by

$$\frac{BU_{EOL}}{BU_{1.03}} = \frac{2 \times cycle}{cycle + 1}$$

to take into account the fuel reshuffling in a real reactor core [8]. An additional calculation up to the end of life (EOL) burnup is used for the evaluation of the material composition at EOL. These material compositions are finally used for the scenario design performed in MS EXCEL.

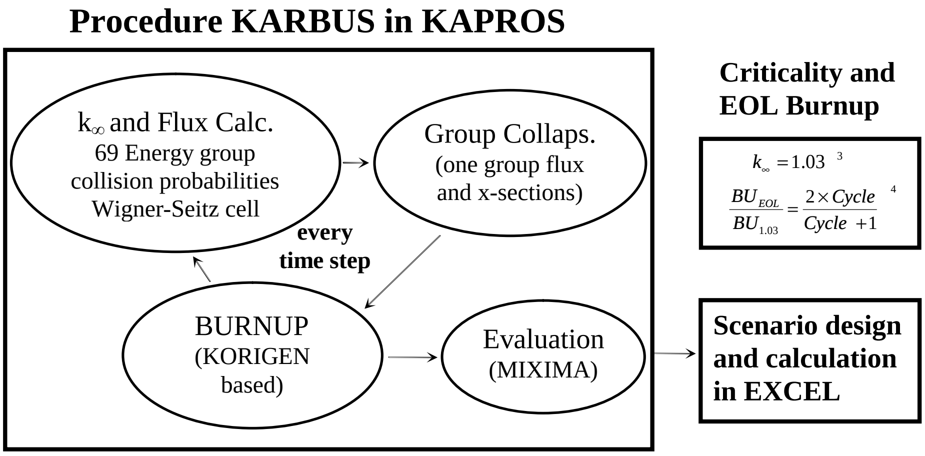

Fig. 1: Schematic diagram of the calculation process

The Scenarios

The Plutonium production will be investigated for 4 different scenarios. The once-through scenario (direct disposal) is the upper limit for the Plutonium production. Idealized single and double Plutonium recycling scenarios provide the lower limits. Additionally a close to reality scenario which represents the situation in Germany is presented. This situation is characterized by an average MOX use of about 15% in the core and a limited reprocessing of roughly 40% of the used UOX fuel due to the stop of reprocessing in 2005.

The scenarios are characterized by the following boundary conditions:

- *Once-through scenario (OT)*

  The burnup over the complete reactor operation period rises by roughly 1 GWd/tHM per year [9] and the starting value in the end of the seventies was between 27 and 33 GWd/tHM [10]. This leads to an estimated time averaged burnup of 41 GWd/tHM over the complete reactor operation period. This burnup is achieved with an initial enrichment of 4% in the reactor use in 949 days in 3 cycles. The average linear pin power is 200W/cm. This value is varied over the 949 days from 150% at begin of life (BOL) to 50% at end of life (EOL).

- *Single Plutonium recycling (MOX1)*

  The burnup structure, the cycle data and the average linear pin power are identical to the once-through scenario. The following times are defined for the reuse of Plutonium in MOX1 fuel: 3 years for storage in the nuclear power plant for cooling, the transport to the reprocessing plant and the storage in the reprocessing plant – 2 years for reprocessing, MOX fuel production and the storage in the nuclear power plant until the insertion into the reactor. This adds up to the over all time of 5 years until reuse. The MOX fuel is produced from roughly 5.4% Pu_{fiss} in depleted Uranium with a fraction of 0.3% U-235. The average linear pin power is varied from 140% (BOL) to 60% (EOL).

- *Double Plutonium recycling (MOX2)*

  The burnup structure, the cycle data and the average linear pin power are identical to the once-through scenario. The following times are defined for the reuse of Plutonium in MOX2 fuel: 10 years for storage in the nuclear power plant for cooling, the transport to the reprocessing plant and the storage in the reprocessing plant – 2 years for reprocessing, MOX fuel production and the storage in the nuclear power plant until the insertion into the reactor. This adds up to the over all time of 12 years until reuse. The MOX fuel is produced from roughly 6.9% Pu_{fiss} in natural Uranium with a fraction of 0.7% U-235. The use of natural Uranium instead of depleted Uranium is necessary to avoid an increase of the Pu_{fiss} content above 7% which could lead to problems in the safety parameters [8]. The average linear pin power is identical to MOX1.

- *Close to reality Plutonium recycling (rMOX)*

  The burnup structure, the cycle data and the average linear pin power are identical to the once-through scenario. The following times close to reality are defined for the reuse of Plutonium: 8 years for storage for cooling, the transport to reprocessing and storage in the reprocessing plant – 5 years for reprocessing, MOX fabrication and the storage before insertion into the reactor. This adds up to the over all time of 13 years until reuse. The MOX fuel is produced from roughly 5.8% Pu_{fiss} in depleted Uranium with a fraction of 0.3% U-235. The average linear pin power is identical to MOX1. The starting time of the MOX use is calculated and averaged from the German reactor operation data to 13.5 years. The average MOX content in the reactor park is 17.5% in every core. The available separated Plutonium amount is roughly 70 t from the reprocessing of 6970 t burnt Uranium oxide fuel. This separated Plutonium amount will be burnt in roughly 10 years of MOX use under the given conditions.

The time dependent behaviour of k_∞ versus burnup for the different used fuel materials is shown in Fig. 2.

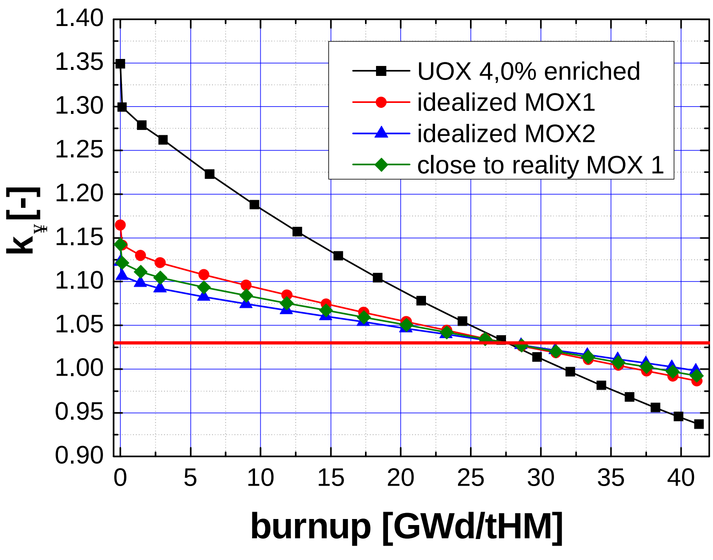

Fig. 2: Burnup dependent k_∞ evolution for the different fuel materials

To collocate the different fuels in one core all curves for k_∞ versus burnup have to meet at k_∞ =1.03 at the identical burnup. Only under this conditions all fuels can be mixed in one hypothetical reactor core in the scenario design and calculation in EXCEL. If this conditions would not be fulfilled a full core calculation would be needed to care for the burnup behaviour. The difference of 3% between criticality and the used k_∞ limit accounts for the losses in a real core configuration.

Lifetime by Law

The following amounts of the residual Plutonium are created during the regular operation of the German reactor park to produce the net electric energy amount of roughly 220TWd fixed by law or the resulting thermal energy amount of 666 TWd gross.

The time dependent accumulated Plutonium mass for the different scenarios is shown in Fig. 3. In the once-through (squares) scenario the Plutonium mass rising linearly due to the used approximation, time averaged burnup. After the regular lifetime when 100% of the fixed electric energy is produced there are about 160 tons of Plutonium accumulated. The Plutonium mass is rising similarly in the single MOX scenario (circles) for the first roughly 20% then the slope is due to the reuse of Plutonium smaller than for the once-through scenario. At the end of the reactor operation period the Plutonium amount is reduced by 25% or more than 40 tons. In the case of the double Plutonium (MOX2 scenario) recycling (triangles) the Plutonium amount is reduced by roughly 35 % or more than 50 tons. In the close to reality MOX scenario (diamond) the MOX use starts when already about 40 % of the electricity is produced. At this point there is a break in the slope of the Plutonium production due to the reuse. The next break is at about 70 % of produced electricity where the reuse of Plutonium is stopped because no separated Plutonium is available anymore due to the termination of reprocessing in the year 2005. The residual Plutonium amount is reduced for the close to reality MOX scenario by about 15% or more than 20 tons in the German reactor park. This result could be improved by re-entry into the reprocessing of burnt Uranium oxide fuel and a result close to the result for the idealized single MOX scenario could be reached (see extrapolation, dotted line).

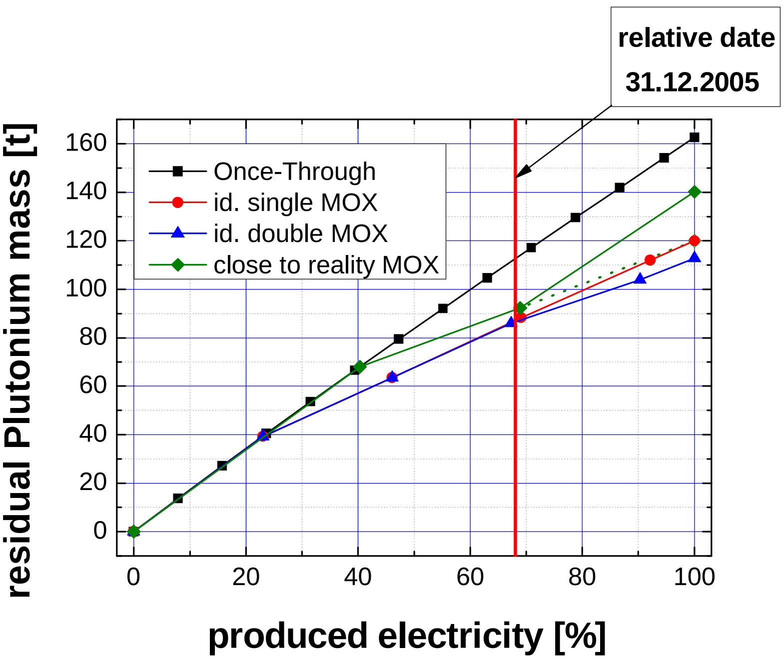

Fig. 3: Residual Plutonium mass for the different scenarios

Lifetime Extension

A postulated lifetime extension for 10 years for the German reactor park is defined in the following way: The electric energy produced in the five years between 2000 and 2005 in the 17 end of 2005 still operating nuclear power plants is doubled. This definition leads to an additional energy production of roughly 80 TWd net. The thermal energy production is rising from 666 TWd in 32 years to 900 TWd in 42 years. The average burnup is increased to 49 GWd/tHM instead of 41 GWd/tHM due to the fact of the already mentioned rise in burnup of about 1 GWd/tHM per year [9].

The energy production is increased by roughly 35%. The accumulated Plutonium masses after this time period of Plutonium are changed in the following way: In the once-through scenario additional 22% or roughly 36 tons of Plutonium are created, in the single MOX scenario (MOX1) arise 20% or 24 tons more Plutonium. In the double MOX scenario (MOX2) only 13% or 15 tons of Plutonium are created additionally. Finally 27% or 38 tons more Plutonium arises for a close to reality German scenario with termination reprocessing. Due to these numbers especially in the case of a lifetime extension a re-entry into reprocessing should be discussed. All scenarios show the identical tendency of under proportional Plutonium production compared to the additional energy production. This is a direct consequence of the higher averaged burnup in the case of a lifetime extension. Only the minor actinide production is over proportional. There will be about 45% more Americium for all scenarios and about 50% more Curium.

Plutonium Reduction and Quality

Finally the reduction of Plutonium and the change in the Plutonium composition due to a double reuse of Plutonium in the form of MOX fuel will be discussed.

The time dependent evolution of the relative Plutonium mass for the production of 1 ton of MOX2 fuel is indicated in Fig. 4. This 1 ton of MOX2 fuel contains about 120 kg Plutonium of the composition indicated by the different colours. The Plutonium amount is burnt to 100 kg during the use of the MOX2 fuel in the reactor. For the production of the 1 ton of MOX2 fuel about 130 kg of Plutonium resulting from the MOX1 use is needed due to the decay of Pu-241 during storage. These 130 kg are the result of about 170 kg of Plutonium which was put into the MOX1 fuel before using it in the reactor core. For the production of this MOX1 fuel is due to the Pu-241 decay roughly 175 kg of Plutonium resulting from the use of 4 % enriched UOX fuel with a cycle time of 949 days needed. To add it up about 175 kg of Plutonium produced in the UOX fuel of the once-through scenario is reduced to about 100 kg after a double reuse at the end of the MOX2 scenario. Consequently the in the once-through scenario produced Plutonium is reduced by more than 40% by the double reuse in MOX fuel. This fact shows the over all potential of Plutonium reduction in the case of unlimited double (or multiple) MOX use.

Additionally the content of Pu-239 is reduced by about 60% in this time compared to the Plutonium composition resulting of the once-through scenario with 4.0% enriched UOX fuel. Thereby the proliferation risk is reduced significantly because of the reduction of the content of fissile Plutonium isotopes.

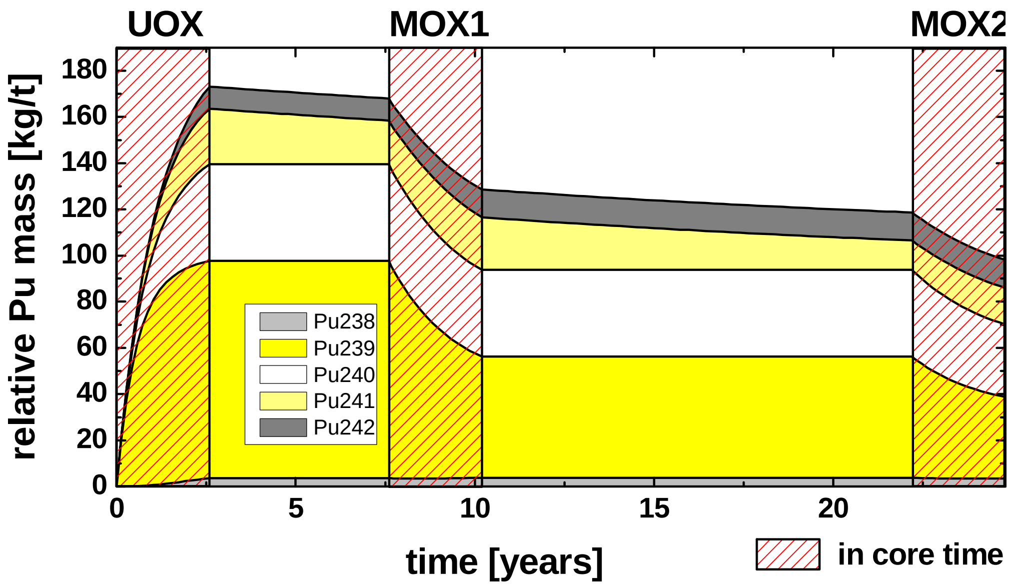

Fig. 4: Relative Plutonium mass needed fort he production of 1 ton of MOX 2 fuel

Conclusions

Basically it has to be mentioned that all presented calculations apply averaging over the German reactor park where every reactor core composition and every cycle is individual. The investigated scenarios are nevertheless reliable estimations of the Plutonium production in the German reactor park under changing boundary conditions. The estimation of the accumulated Plutonium mass for a scenario close to the reality in Germany shows the benefit of reprocessing and MOX fuel use. A significant reduction of the Plutonium amount by roughly 20 tons is achieved during the limited time period of MOX use. A part of the possible achievement is lost due to the termination of reprocessing by law in 2005. Without this limiting condition a reduction of about 40 tons would be achievable.

A postulated lifetime extension leads for all scenarios to an under proportional amount of Plutonium produced compared to the additionally produced amount of energy. While the energy production rises by about 35 % the Plutonium amount is only increased by 13 to 27 % depending on the used scenario. An additional overview on the results for the different scenarios is given in Tab. 1. One fact has to be highlighted here: In the case of a lifetime extension and simultaneously a re-entry into reprocessing and continuation of single MOX use leads to the identical final Plutonium amount as for the close to reality scenario defined by the actual situation in Germany.

The Plutonium mass is reduced by roughly 40% with the double recycling of the MOX2 scenario compared to the Plutonium amount resulting from the UOX fuel use in the once-through case. Additionally the Plutonium composition is changed in such a way that the proliferation risk is significantly reduced due to the reduction of the fraction of the fissile Plutonium isotope Pu-239 to roughly 40%. The amount of Pu-239 is reduced by about 60% compared to the Plutonium composition remaining at the end of life of the UOX fuel.

	Once-Through (OT)	Single MOX (MOX1)	Double MOX (MOX2)	Close to reality MOX (Creal)
Lifetime by Law (LL)				
tons	~160	~120	~110	~140
compared to OT	100%	-25%	-35%	-15%
Lifetime Extension				
tons	~36	~24	~15	~38
compared to LL	+22%	+20%	+13%	+27%
Over all after 42 years				
tons	~196	~144	~125	~178
compared to Creal LL	140%	103%	90%	127%

Tab. 1: Overview on the results for the different scenarios

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