ON THE USE OF EXISTING HIGH ENRICHED MOX FUEL IN AN EXPERIMENTAL ADS

C.H.M. Broeders[1], J. Cetnar[2,3], R. Dagan[1], W. Gudowsky[3], A. Travleev[1]

[1]*Forschungszentrum Karlsruhe,*
Institut für Reaktorsicherheit,
P.O. Box 3640, 76021 Karlsruhe, Germany

[2]*Faculty of Physics and Nuclear Techniques,*
University of Mining and Metallurgy
30 059 Cracow, Poland

[3]*Department of Nuclear and Reactor Physics,*
Royal Institute of Technology,
100 44 Stockholm, Sweden

The work presented is part of the FZK and RIT contributions to the investigations for the assessment of the possibility to use existing highly-enriched MOX fuel in an ANSALDO-ENEA design for an experimental ADS (XADS) with lead bismuth (LBE) coolant, studied in the PDS-XADS Project of the 5. Framework Program of the European Community. Use of slightly modified existing fuel assemblies, of fuel pins, of fuel pellets and of reprocessed fuel is considered. Neutron physics, including burn-up analysis are presented. Use of SNR300 fuel assemblies appears feasible if technical and logistical constraints can be solved. SPX fuel pins or pellets also may be utilized, but due to the lower fissile enrichment a larger core is required. An interesting alternative is the utilization of both SPX and SNR300 pellets in fuel assemblies with identical outer dimensions, but with different lattice parameters. The preliminary burn-up analysis for a reference core with SNR300 fuel assemblies with Monte Carlo and deterministic methods show a burn-up reactivity loss of 6 to 7 pcm per full power day, corresponding to a reactivity loss of about 2% per year at 70 to 80% duty cycle.

1. Introduction

The work presented is part of the FZK and RIT contributions to the investigations for the assessment of the possibility to use existing fresh highly-enriched MOX fuel in an ANSALDO-ENEA design for an experimental ADS (XADS) with lead bismuth (LBE) coolant, studied in the PDS-XADS Project of the 5. Framework Program of the European Community. A first very preliminary assessment to utilize existing SNR300 fuel assemblies in an experimental ADS was presented in [1]. In Appendix 5 of the European Roadmap for ADS Devel-

opment [2] a more detailed analysis was performed, considering available fuel assemblies (FA) both from the fast breeder programs in Germany (SNR300) and France (SPX). Some main results in [2] are:

- From technological point of view it is feasible to use SNR300 and SPX FA.
- For SPX fuel a preliminary assessment was made to disassemble the FA and to utilize the fuel either in the rods or as pellets. Both options are feasible if facilities to handle this fuel stay available. The high Americium content in this old MOX fuel is not a major problem.
- Both SNR300 and SPX fuel pins contain axial blankets in bottom and top areas.
- SNR300 FA have higher enrichments than the SPX FA because of the smaller core.
- Fabrication periods: SNR300 FA between 1978 and 1985. SPX first core between 1978 and 1984, second core between 1985 and 1988.

From these considerations no other significant differences than the enrichments are to be expected in the utilization of SNR300 and SPX fuel. After a short characterization of the existing fuels in section 2, in section 3 the neutron physics analysis is described for the available fuel options. First burn-up analyses for the reference design of a LBE cooled XADS with SNR300 FA are presented in section 4. More comprehensive information may be found in references [3,4].

2. Characterization of existing fuel

A good characterization of the SNR300 and SPX fuels may be found in reference [2]. A summary of construction details and of fuel compositions as predicted for the year 2010 of SNR300 and SPX fuel is given in references [3,4]. The available fresh FA have fissile enrichments varying from 12.2% to 15.8% for the SPX fuel and from 18.8% to 26.4% for the SNR300 fuel. These enrichments may be a good basis for the construction of an experimental ADS with conventional MOX fuel in a first operation stage.

3. Neutron physics core simulations

In the next sections exploratory neutron physics simulations of XADS core configurations with Lead Bismuth Eutectic (LBE) cooling will be discussed. The multi group cross sections were prepared within the KAPROS/KARBUS modular code system starting from a 69 group master library, mainly based on the JEF2.2 evaluated data library. In most cases standard collapsing from 69 to 12 groups was applied. The flux calculations were carried out with the diffusion code CITATION and the transport code TWODANT. To confirm the results

obtained by the deterministic codes, the core simulation was also done by the MCNP code with the same homogenized cylindrical models from the deterministic multi-group calculations for selected cases. The agreement between the results of the Monte Carlo code and the deterministic codes was good, see references [3,4].

3.1. *Core with SNR-300 FA cooled with Lead Bismuth Eutectic*

For the SNR-300 fuel the existing FA may be arranged in a small core containing 66 FA with 2 enrichments. The radial reflector and the inner tube are filled with homogeneous mixture of LBE and structure material in proportion depending on the specific core design. The influence of the reflector size on the criticality was studied in more detail. It was found that about 70 cm is needed before reaching an asymptotic behavior. The results indicate that the SNR300 fuel is well suited for use in the envisaged XADS project. The original FA, including axial blanket zones, may be used from the neutron physics point of view. However, the specific construction details must be taken into account in the XADS design.

3.2. *Core with SPX fuel cooled by Lead Bismuth Eutectic (LBE)*

The existing Super Phenix (SPX) fuel is considered intensively in the XADS project. The ANSALDO XADS core design is based on reprocessed SPX fuel with increased fissile fraction, compared to the existing SPX fuel composition. In this section the possibilities to use SPX rods or pellets for the ANSALDO XADS design proposals with LBE coolant are discussed. In this case the fuel refabrication for the XADS could be avoided. The proposed core design contains 198 FA in 6 full fuel rings, whereas the ANSALDO model consists of only 120 FA.. The calculations show that the SPX fuel is not so well suited for direct use in an XADS. The dimensions of the existing core and the relatively low enrichments lead to the conclusion that the SPX pellets may be used in an XADS core with $\approx$ 200 FA., see references [3,4] for more details.

3.3. *ANSALDO core design with two existing enriched fuel types*

It is of interest to check the feasibility of using the existing SNR300 and SPX fuels to avoid the reprocessing costs of fuel fabrication. In the following, three constraints are satisfied: the criticality level is around 0.97, the number of subassemblies is 120 and the subassembly geometry is identical with the original ANSALDO design. From several possibilities, two representative configurations are discussed in references [3,4] to emphasize the balance between lower costs, improved neutron physics characteristics and thermal–hydraulics aspects. Data and layout of the most promising proposal is summarized in figure 1 and table 1.
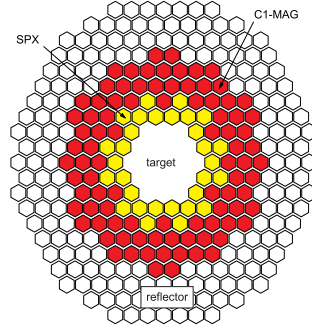
4

Figure 1. ANSALDO core layout for a two enrichment option. The target zone, represented by LBE mixed with structure material; SPX – most enriched SPX fuel; C1_MAG – SNR fuel with 19.5% enrichment, reflector is represented by homogenized LBE and structure mixture

Table 1. Criticality and power densities of a selected design for a 80MW$_{th}$ ANSALDO based XADS core. The power densities refers to the "source on" option

Number of SPX assemblies	30
Number of SNR assemblies	90
K_{eff}	0.9717
Multiplicity with source on	0.9722
Peak linear power (W/cm)	125.0
Mean linear power in SPX assembly (W/cm)	82.4
Mean linear power in SNR assembly (W/cm)	89.7

30 subassemblies with original SPX pellets are introduced and the rest 90 subassemblies contain MOX with 19.5% SNR fuel pellets. These assumptions imply reprocessing of the SNR300 fuel. The first analysis of this core design clearly shows that the available MOX fuel pellets may be used for the design of an acceptable XADS core. A very interesting solution is the use of SNR fuel pellets with 5 mm outer diameter in an assembly with the same outer dimensions as the ANSALDO FA design for SPX pellets with 7.14 mm outer diameter. This option could be investigated in more detail in a next stage.

4. Burn-up calculations for a core with SNR300 fuel

First preliminary burn-up investigations were performed for the reference design of a LBE cooled XADS with SNR300 FA. For this purpose, two alternative methods were applied:
- Full Monte Carlo burn-up calculations with the MCB1C Code, performed by RIT Stockholm
- Deterministic multi-group depletion calculations, performed by FZK Karlsruhe.

4.1. *Burn-up investigations with the Monte Carlo code MCB1C*

The burn-up calculations were preformed by using the MCB [5] code in a geometry model of the XADS reactor using the adapted (R-Z) geometry version provided by FZK with 24 burnable zones (3 radial times 8 axial sections). The neutron source is represented by a surface source file (RSSA) that was obtained by a collection of all neutrons leaking from the LBE target during an MCNPX simulation of a 600MeV proton beam interaction with the target in a standalone bare target model. In order to assess the required reactor core parameters, the Monte Carlo method of neutron transport was applied using the MCNP based codes MCNPX and MCB1C, with temperature dependent cross section libraries of the MCB system. Two modes of calculations were applied: First, the fixed source mode of MCNPX in a bare target system to produce the neutron source for burn-up calculations in MCB and to obtain core power distribution and radiation damage. Second, the burn-up mode of MCB to calculate the system evolution with time over 3 years of the 80MW_{th} thermal power irradiation. In general, the JEF2.2 cross section libraries were used in the current calculations, whereas for nuclides of lead that are missing in JEF2.2 the JENDL3.2 data were used. The cross section at power temperatures 1200K for fuel and 900K for target were used. For the calculation of K_s an integral approach has been applied. MCB calculates the thermal power released per one source particle and adjusts the source intensity to keep power at the user specified level. The core actual thermal power consists of direct radiation heating, including neutron KERMA heating and gamma heating, as well as decay heating – mostly from decays of short lived fission products. In our case the decay heating accounts for about 3.0 MW_{th} while the remaining 77.0 MW_{th} comes from prompt radiation interaction with matter. The total power, however, neglects the energy release into the target in the high-energy particle transport. For the purpose of comparison with calculations that are normalized to fission energy we have assessed the energy release per one fission event by dividing the total heating by the number of fission events resulting in 216.5 MeV per fission. However, the obtained value should not be understood as the energy of one fission event since it includes all energy releasing processes taking place in the system.

4.2. *Burn-up investigations with the deterministic multi-group code system KAPROS/KARBUS*

The modular code system KAPROS contains several options to perform burn-up investigations. The basic module BURNUP is based on the formalisms of the KORIGEN code [6]. The required one-group data for the evolution calculations can be provided within the KAPROS system with the help of best estimate weighting spectra, applied to the macroscopic multi-group zone dependant cross sections. The current 69 group master data library contains multi-group cross sections for activation analyses for about 800 isotopes, including more than 160 isotopes with data for full multi group transport calculations. For this first XADS burn-up investigations the same calculation scheme was applied as for the IAEA ADS benchmark for Th/U^{233} fuel [7]. The applied spallation neutron source was similar as in the IAEA benchmark: constant source in the central fuel assembly position with total extension of 30 cm symmetric to the center. The energy spectrum of the source was the same as in [7]. The reactor model is identical with the (R-Z) geometry of the MCB1C case. Calculations were performed for 12 and 69 groups based on JEF2.2 and JEFF3.0 evaluated data. The power generation in this deterministic burn-up calculations is based on 210 MeV energy release per fission. The results for the reactivity for the system, driven by the external source (source on), K_s, are based on consistent calculations of the ratio of neutron production to neutron losses.

4.3. *First comparisons of RIT and FZK results*

In this section first comparisons of RIT results with Monte Carlo methods and of FZK results with deterministic methods are presented. The comparisons are performed with a 12 group constant library derived from a 69 group master library; mainly based on the JEF2.2 evaluated data file. A comparison of the time evolution of the criticality for source on/off states is presented in figure 1. The "source on" results are obtained from the calculations with external source, whereas the results for "source off" come from homogenous eigenvalue calculations.
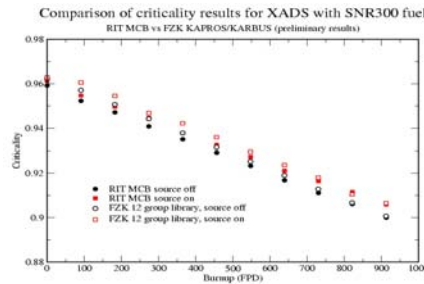

Figure 1   Comparison of RIT Monte Carlo and FZK deterministic results for burn up dependant criticality values for XADS with SNR300 fuel. Source on/off states are plotted.

We may observe a satisfactory agreement between the RIT and FZK results. The discrepancies decrease with increasing burn-up. Although the source representation is quite different in the RIT and FZK investigations, the behaviour of the reactivity for source on/off is similar in both cases: the value for source on is slightly higher than for source off and the difference has a tendency to increase with increasing burn-up. The reactivity loss in pcm per full power day shows agreement better than 10% and amounts 6 to 7 pcm with a slowly decreasing tendency with burn-up. These values are rather high and lead to a reactivity decrease of $\Delta k_{eff} \approx 2\%$ per year at 70..80% duty cycle. Figure 2 shows comparisons between RIT and FZK results for the changes in the heavy metal inventories of the main isotopes in the core.
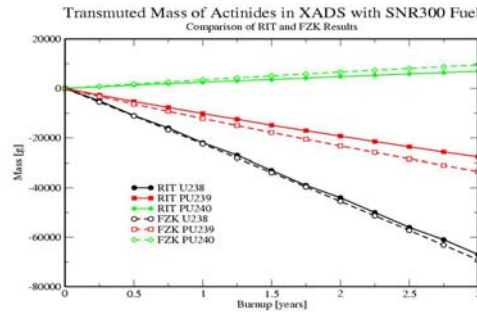

Figure 2. Comparison of RIT Monte Carlo and FZK deterministic results for burn up

Generally, the results show that nuclides that are being reduced in mass are U^{238}, Pu^{239}, U^{235} and Am^{241}, other nuclides usually are being build-up. The differences in the heavy metal inventory changes in the RIT and FZK results increase if the build-up of the isotopes becomes more complicated by multiple transitions. The differences for the individual isotopes have to be analyzed in more detail.

5.   Summary

Several options for the utilization of the existing high enriched fuel from the European fast breeder programs SNR300 and SPX in the core of an XADS have been investigated. In these studies the use of slightly modified fuel assemblies, of fuel rods and of pellets have been considered. From the neutron physics point of view the reference core with SNR300 fuel assemblies is feasible. The two level enrichment strategy allows for low peak factor and a flattened spatial flux distribution. For the SPX fuel based model an optimization procedure is necessary to favor either the option of fabricating new fuel (ANSALSO model) or to remain with the existing fuel and to deal with the consequences of a larger system. The combination of two fuel pellet types within fuel assemblies of the

8

ANSALDO core design seems to be feasible and might be the best solution if technical and logistics problems can be solved. First preliminary burn-up calculations with Monte Carlo and deterministic methods for the SNR300 fuel reference core show reasonable agreement for important parameters. The differences in the evolution of minor actinides are larger and have to be analyzed in more detail. The reactivity loss per full power day amounts 6 to 7 pcm and is slowly decreasing with burn-up. These values are rather high and lead to a reactivity decrease of $\Delta k_{eff} \approx 2\%$ per year at 70..80% duty cycle.

Acknowledgments

References

1. C.H.M. Broeders, "A comparison of some neutronics characteristics of critical reactors and accelerator driven subcritical systems", Proc. 5. Int. Inf. Exch. Meeting Mol P&T, 25-27.11.1998
2. R.J.M. Konings and G. Mühling, "Fuel of the ADS", Appendix 5 to European Roadmap for developing ADS for nuclear waste incineration, April 2001
3. C.H.M. Broeders et. al, "Assessment of the possibility to use existing highly-enriched MOX fuel", PDS-XADS Project Delivery D10, App. A
4. C.H.M. Broeders et. al, "On the use of existing highly-enriched MOX fuel in an experimental ADS", AccApp'03. San Diego (2003)
5. J. Cetnar, W. Gudowski and J. Wallenius, "MCB: A continuous energy Monte Carlo Burnup simulation code", In "Actinide and Fission Product Partitioning and Transmutation", EUR 18898 EN, OECD/NEA (1999) 523
6. H.-W. Wiese, B. Krieg, "Erweiterung der KORIGEN- Datenbibliotheken und Berücksichtigung der Spaltprodukte aus Spontanspaltungen", Internal FZK report PSF3253 (1996) .
7. C.H.M. Broeders, I. Broeders, "Development and validation of calculation procedures for the neutron physics investigation of accelerator driven subcritical systems", Proc IAEA TCM Argonne (2000)