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# Analysis of the optimal fuel composition for the Indonesian experimental power reactor

*The optimal fuel composition of the 10 MWth Experimental Power Reactor (RDE), to be built by the Indonesian National Nuclear Energy Agency (BATAN), is a very important design parameter since it will directly affect the fuel cost, new and spent fuel storage capacity, and other back-end environmental burden. The RDE is a very small sized pebble-bed high temperature gas-cooled reactor (HTGR) with low enriched uranium (LEU) $UO_2$ TRISO fuel under multipass or once-through-then-out fueling scheme. A scoping study on fuel composition parameters, namely heavy metal (HM) loading per pebble and uranium enrichment is conducted. All burnup, criticality calculations and core equilibrium search are carried out by using BATAN-MPASS, a general in-core fuel management code for pebble bed HTGRs, featured with many automatic equilibrium searching options as well as thermal-hydraulic calculation capability. The RDE User Requirement Document issued by BATAN is used to derive the main core design parameters and constraints. The scoping study is conducted over uranium enrichment in the range of 10 to 20 w/o and HM loading in the range of 4 g to 10 g/pebble. Fissile loading per unit energy generated (kg/GWd) is taken as the objective function for the present scoping study. The analysis results show that the optimal HM loading is around 8 g/pebble. Under the constraint of 80 GWd/t fuel discharge burnup imposed by the technical specification, the uranium enrichment for the optimal HM loading is approximately 13 w/o.*

***Analyse der optimalen Brennstoffzusammensetzung für den Indonesischen experimentellen Leistungsreaktor.*** *Die optimale Brennstoffzusammensetzung des von der indonesischen National Nuclear Energy Agency (BATAN) geplanten 10 MWth experimentellen Leistungsreaktors (RDE) ist ein wichtiges Ausgestaltungsmerkmal, da dadurch direkt Brennstoffkosten, Lagerkapazitäten für neue und abgebrannte Brennelemente sowie Umweltbelastungen betroffen sind. Der RDE ist ein kleiner gasgekühlter Hochtemperatur-Reaktor (HTGR) mit niedrig angereichertem Uran (LEU) $UO_2$ TRISO Brennstoff. Eine Voruntersuchung der Parameter der Brennstoffzusammensetzung, wie die Schwermetall-Beladung und die Urananreicherung eines Kugelbrennelements wurde durchgeführt. Alle Abbrand-, Kritikalitäts- und Gleichgewichtsberechnungen wurden mit Hilfe von BATAN-MPASS, einem Brennstoffmanagementcode für Kugelhaufenreaktoren durchgeführt. Das von BATAN ausgestellte Dokument für die RDE-Benutzeranforderungen wird verwendet um die wichtigsten Auslegungsparameter und ihre Beschränkungen abzuleiten. Die Voruntersuchung wurde durchgeführt über einen Bereich der Urananreicherung von 10 bis 20 w/o und einer Schwermetall-Beladung von 4 g bis 10 g/Kugel. Die Beladung mit spaltbarem Material pro erzeugte Energieeinheit (kg/GWd) wurde als objektive Funktion für die Voruntersuchung verwendet. Die Ergebnisse der Analyse zeigen, dass die optimale Schwermetall-Beladung bei etwa 8 g/Kugel liegt. Aufgrund der von den technischen Spezifikationen auferlegten Beschränkung von 80 GWd/t für den Entladebrand liegt die Urananreicherung bei optimaler Schwermetall-Beladung bei etwa 13 w/o.*

## 1 Introduction

The National Nuclear Energy Agency of Indonesia (BATAN) is launching a plan (2014) to build an Experimental Power Reactor (*Reaktor Daya Eksperimental, RDE*) [1] in the Agency's largest Research Center site, i.e. the Puspiptek Complex, Serpong, South Tangerang, Banten, as a first strategic milestone for the introduction of large scale nuclear power plant fleets into the country. The main objective of the plan is to demonstrate safe and reliable electricity and process heat generation from a nuclear reactor. According to the User Requirement Document [1] issued by BATAN, the RDE adopted a very small sized pebble-bed high temperature gas-cooled reactor (HTGR) with a thermal output of 10 MWth, fueled with low enriched uranium (LEU) $UO_2$ TRISO fuel under multipass or once-through-then-out (OTTO) fueling scheme. The thermal heat generated in the core is transferred to steam generator (for electricity generation) and a heat utilization plant via an intermediate heat exchanger (IHX). The use of IHX is expected to ensure a high degree of plant safety especially the steam/water ingress events can be avoided. As will be shown later, the document provides general main specifications of the RDE, however, many detail design parameters on the core dimension, fuel composition etc. are given in term of ranges of value which should be further optimized during the conceptual, basic and detail design phases.

An optimal fuel composition in the operation of a pebble-bed HTGR is a very important design parameter since it will directly affect the fuel cost, new and spent fuel storage capacity as well as other back-end environmental burden. A scoping study on the fuel composition parameters, namely heavy metal (HM) loading per pebble and uranium enrichment is conducted. The main goal of this study is to obtain optimal ranges of HM loading per pebble and uranium enrichment for the RDE design. HM loading per pebble strongly affects the neutron moderation (core neutron spectrum) while uranium enrichment is correlated directly with the achievable discharge burnup. The present work is expected to contribute in providing an optimal fuel composition for the RDE, however, only HM loading per pebble and uranium enrichment are considered in the analysis. Nevertheless, since the ranges of the parameters considered are adequately wide, not only the optimal fuel composition value but also the trend and im-

Table 1. *Main design parameters and constraints of the 10 MWth RDE*

| Design Parameters | Specifications Issued by BATAN | Present Analysis |
|---|---|---|
| Thermal Power (MW) | 10 | 10 |
| Core Diameter (m) | < 2.5 | 1.8 [2] |
| Core Height/Diameter Ratio | >1.1 | 1.1 (Height = 1.97 m) |
| Ave. Core Power Density (PD, W/cm$^3$) | $2.0 \leq PD \leq 3.0$ | 2.0 (Max. Core Vol.) |
| Upper Core Void Height (m) | – | 0.4 [2] |
| Radial Reflector Thickness (m) | – | 0.5 |
| Upper and Lower Reflector Thickness (m) | – | 1.0 |
| $^{235}$U Enrichment (w/o) | ≤ 17 | 10–20 (LEU) |
| HM Loading (g/pebble) | ≤ 20 | 4–10 |
| Ave. Discharge Burnup (GWd/t) | 80 | 80 |
| Fueling Scheme | Multipass/OTTO | Multipass (5 passes [2]) |
| He Inlet/Outlet Temp. (C) | 250/700 | 250/700 |
| He Inlet Pressure (MPa) | 3 | 3 |

Table 2. *Standard data for pebble fuel element cell calculation*

| TRISO coated particle fuel | | |
|---|---|---|
| Kernel | material | ($^{235}$U/$^{238}$U)O$_2$ |
| | diameter (μm) | 500 |
| | density (g/cm$^3$) | 10.9 |
| Coatings | material | PyC/PyC/SiC/PyC |
| (from inner) | thickness (μm) | 90/40/35/35 |
| | density (g/cm$^3$) | 0.9/1.85/3.2/1.85 |
| Pebble fuel element | | |
| Fuel matrix | material | graphite |
| | diameter (cm) | 5 |
| Outer layer | material | graphite |
| | thickness (cm) | 0.5 |
| Fuel element | diameter (cm) | 6 |
| Few group structure | | |
| Upper bound (eV) | Lower bound (eV) | Range |
| $10^7$ | $1.11 \times 10^5$ | fast fission |
| $1.11 \times 10^5$ | $2.90 \times 10^1$ | slowing down |
| $2.90 \times 10^1$ | 2.38 | resonance |
| 2.38 | ~ | thermal |

pact of the two design parameters on the core neutronics and burnup characteristics can be obtained.

## 2 RDE technical specifications

In Table 1, the main design parameters and constraints of the RDE are listed. The parameters and constraints shown in the second column of the table were taken from the URD issued by BATAN. The thermal output, discharge burnup and the coolant inlet/outlet temperature and pressure are already fixed. As for the core dimension, three design constraints are imposed, that is, the maximum core diameter, minimum height/diameter ratio and average core power density. On the other hand, as for the fuel composition, only the maxi-

Table 3. Nuclides used in BATAN-MPASS code

| | |
|---|---|
| Heavy metals | $^{232}$Th, $^{233}$Pa, $^{233}$U, $^{234}$U, $^{235}$U, $^{236}$U, $^{237}$Np, $^{239}$Np, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{242}$Pu |
| Fission products | $^{83}$Kr, $^{95}$Zr, $^{95}$Mo, $^{97}$Mo, $^{99}$Tc, $^{101}$Ru, $^{103}$Ru, $^{103}$Rh, $^{105}$Rh, $^{105}$Pd, $^{106}$Pd, $^{109}$Ag, $^{113}$Cd, $^{131}$I, $^{131}$Xe, $^{133}$Xe, $^{135}$Xe, $^{136}$Xe, $^{133}$Cs, $^{134}$Cs, $^{141}$Pr, $^{143}$Pr, $^{143}$Nd, $^{145}$Nd, $^{146}$Nd, $^{147}$Pm, $^{148\,m}$Pm, $^{148\,g}$Pm, $^{147}$Sm, $^{148}$Sm, $^{149}$Sm, $^{150}$Sm, $^{151}$Sm, $^{152}$Sm, $^{153}$Eu, $^{154}$Eu, $^{155}$Eu, $^{155}$Gd, $^{156}$Gd, $^{157}$Gd, Non-saturating FP |
| Moderators | $^{12}$C, $^{16}$O |
| Poisons | B, Impurity in C |

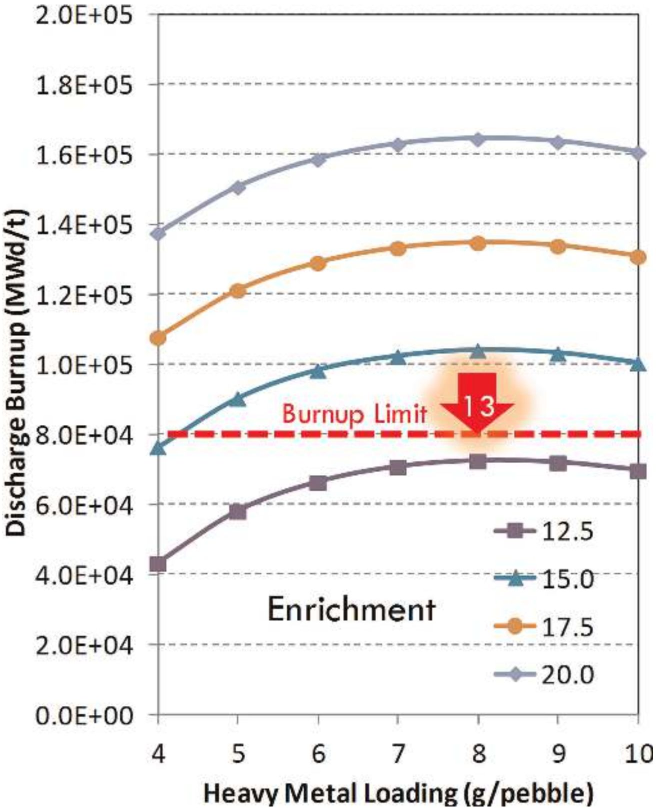

Fig. 2. Average discharge burnup as function of heavy metal loading and uranium enrichment

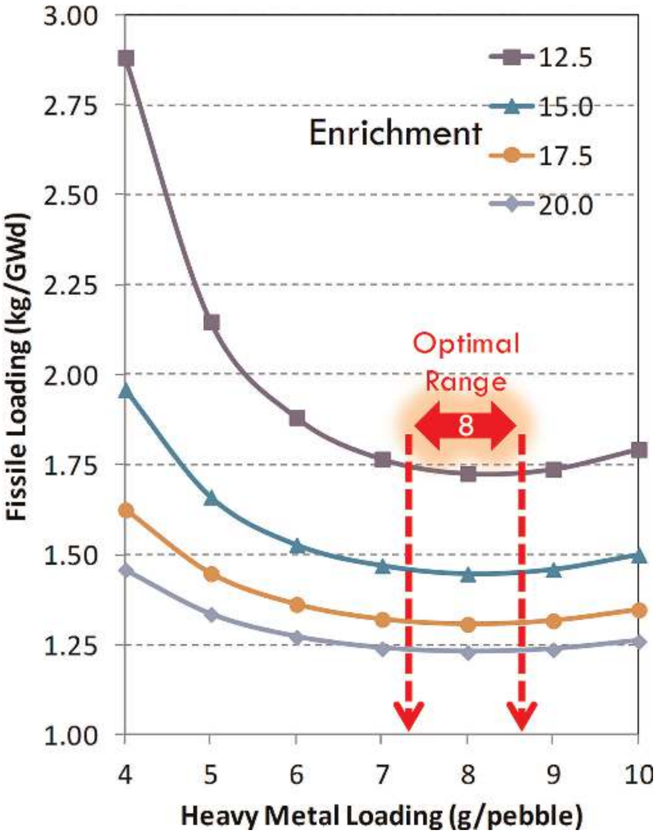

Fig. 1. Fissile loading requirement as function of heavy metal loading and uranium enrichment

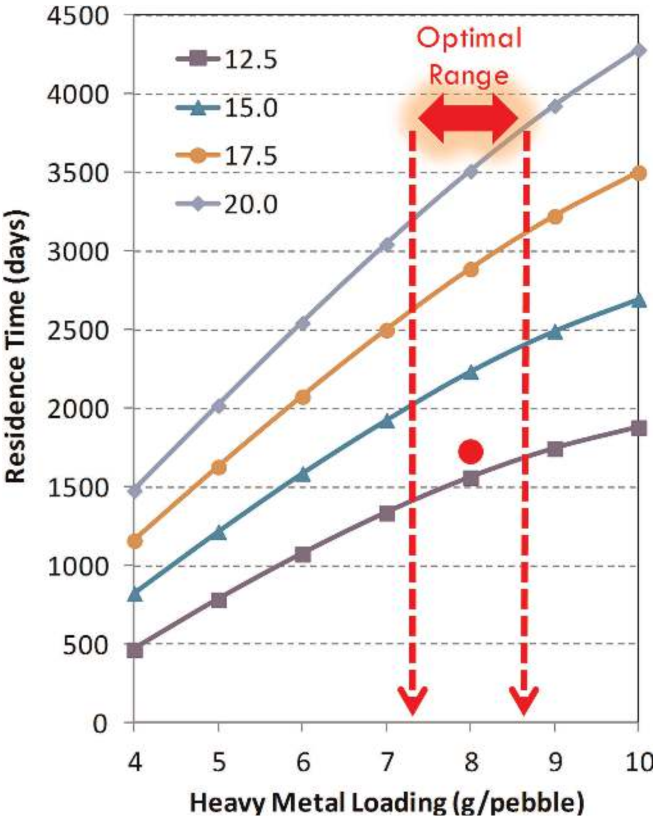

Fig. 3. Pebble fuel residence time as function of heavy metal loading and uranium enrichment

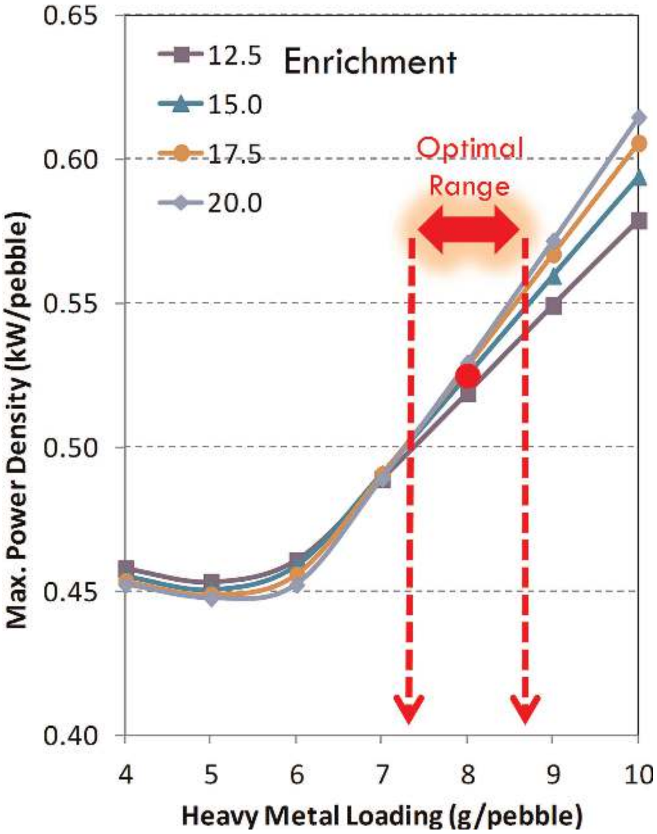

*Fig. 4. Maximum power density as function of heavy metal loading and uranium enrichment*

mum uranium enrichment (17 w/o) and maximum HM loading (20 g/pebble) are imposed.

The third column of Table 1 gives the design parameters taken for the present scoping study. The core diameter is set to 1.8 m (derived from the Chinese 10 MWth HTR-10 [2]) while the core height/diameter ratio and average power density are set to its minimum and maximum value, i. e. 1.1 and 2 W/cm$^3$, respectively, to obtain good neutron economics. The void cavity at the top of the core is necessary and its height is set to be approximately 40 cm [2]. As for the fresh fuel composition, the scoping study is conducted over uranium enrichment in the range of 10 to 20 w/o and HM loading in the range of 4 to 10 g/pebble. Cases of uranium enrichment higher than the maximum design constraint (17 w/o) are also considered for the sake of completeness since the possible maximum uranium enrichment for LEU is 20 w/o. Cases with HM loading less than 4 or higher than 10 g/pebble are excluded through preliminary screening calculations.

The URD issued by BATAN allows the RDE to be operated under the multipass or once-through-then-out (OTTO) fueling scheme. However, OTTO fueling scheme is not included in the present scoping study since from the point of view of axial power peaking factor the multipass fueling scheme is favorable. The multipass fueling scheme is selected for the present study and the number of pass is adopted from the Chinese 10 MWth HTR-10 [2], i. e. 5 passes.

Since detail fuel specification and core-reflector structures and dimensions etc. are not presently available, we assume no boron (equivalent) impurity in the fuel, 50 cm (radial) and 100 cm (axial) thickness of pure graphite reflectors with graphite density of 1.75 g/cm$^3$. For the multipass refueling strategy, we assume no radial zoning.

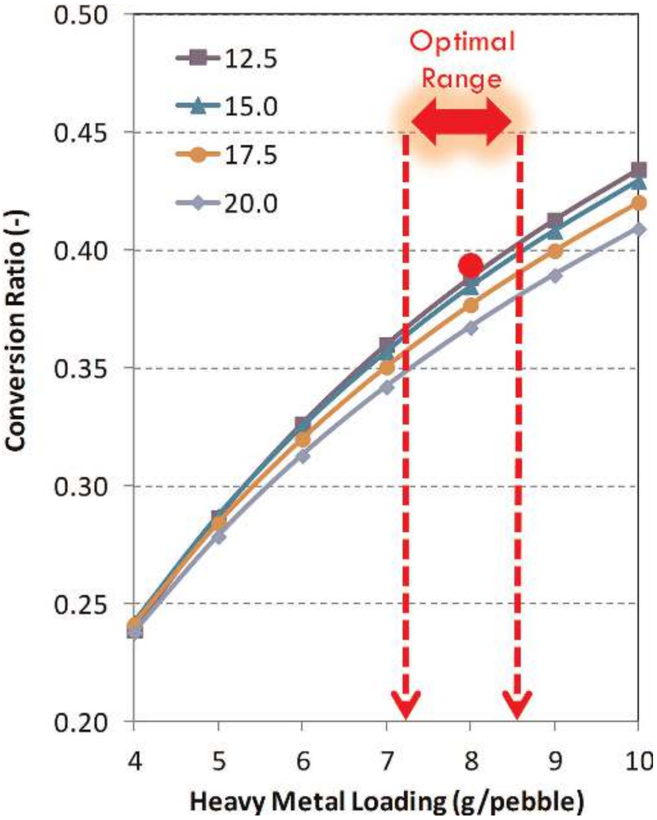

*Fig. 5. Conversion ratio as function of heavy metal loading and uranium enrichment*

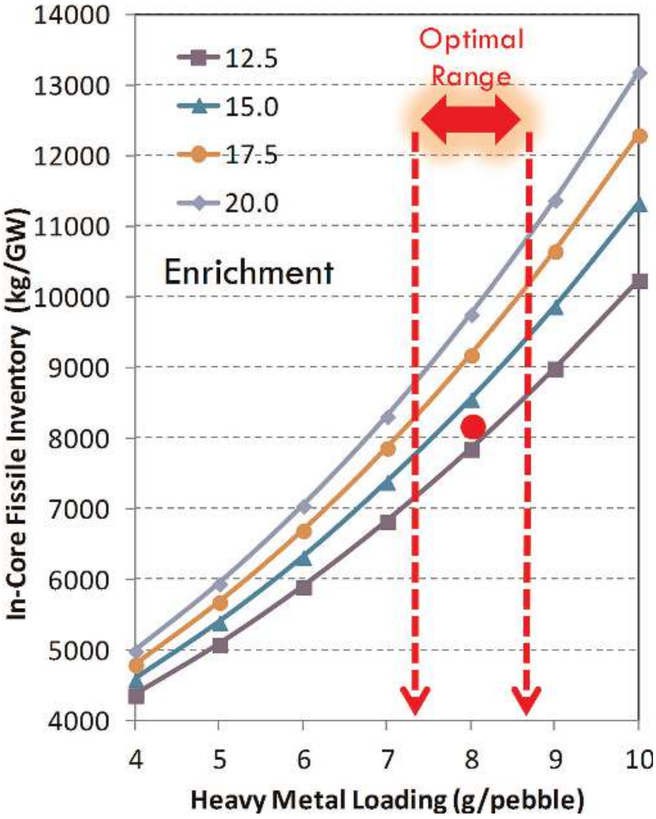

*Fig. 6. In-core fissile inventory as function of heavy metal loading and uranium enrichment*

## 3 Analytical code and group constants

The pebble fuel movement, burnup, core criticality calculations and core equilibrium search are carried out by BATAN-MPASS [3], a general in-core fuel management code for pebble-bed HTGRs, featured with many automatic equilibrium and criticality searching options as well as thermal-hydraulic calculation capability. The code has been validated with the German HTR-Module design, the validation results have also been used as a comparative solution for other code [4].

The TRISO coated particle fuel and pebble fuel element specifications are shown in Table 2. The microscopic cross-sections (4 energy groups, Table 2) and their self-shielding factors as a function of temperature and composition were prepared using several parts of the VSOP code system [5]: ZUT-DGL, THERMOS and GAM. In Table 3, the heavy metals, fission products, moderators and poisons nuclides used in the burnup chain of BATAN-MPASS are listed.

Group constants for the cavity at the top of the core are determined according to the method developed by Gerwin and Scherer [6]. Using their method, different axial and radial diffusion coefficients can be obtained. The detail discussion of the in-core thermal-hydraulic model used in the BATAN-MPASS code was already given by Liem and Sekimoto [7]. By using the core equilibrium search option, all calculation cases converged to an equilibrium core with effective multiplication factor (keff) equals to 1.0 (critical).

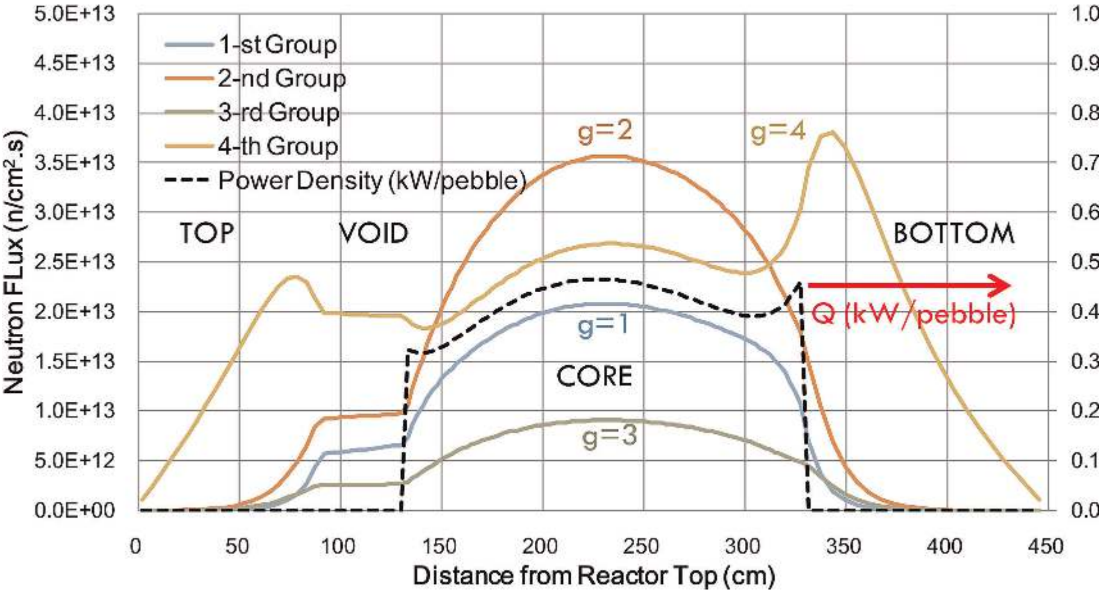

*Fig. 7. Axial distributions of group neutron flux and power*

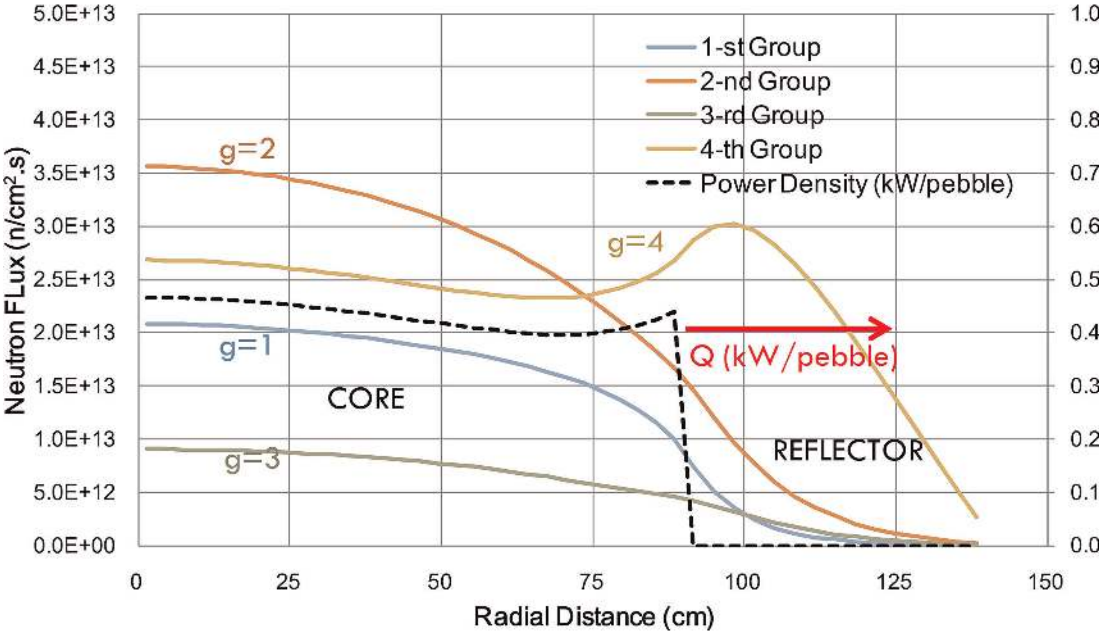

*Fig. 8. Radial distributions of group neutron flux and power*

## 4 Results and discussion

The scoping analysis results are shown in Figs. 1 to 6. Figure 1 shows the fissile loading requirement as a function of HM loading for 4 values of uranium enrichment. The fissile loading requirement per unit energy generated (kg/GWd) decreases as the uranium enrichment increases. For all values of uranium enrichment, one can find an optimal value of HM loading per pebble, which is around 8 g/pebble. This optimal composition also indicates the optimal moderation for the reactor.

Figure 2 shows the pebble fuel element discharge burnup as a function of HM loading for 4 values of uranium enrichment. From the figure, it can be observed an almost linear proportionality of discharge burnup to uranium enrichment. Similar to Fig. 1, for a particular value of uranium enrichment one can find an optimal value of HM loading per pebble, which is also around 8 g/pebble. If the design constraint of 80 GWd/t discharge burnup is imposed then for the optimal HM loading of 8 g/pebble case, the uranium enrichment is found to be around 13 w/o. For the case of optimal HM loading and uranium enrichment of 13 w/o, the pebble fuel residence time in the core is around 4.4 years (indicated by a red dot in Fig. 3).

Figure 4 shows the maximum power density (kW/pebble) as a function of HM loading. This parameter is not too sensitive to the uranium enrichment. For HM loading higher than 6 g/

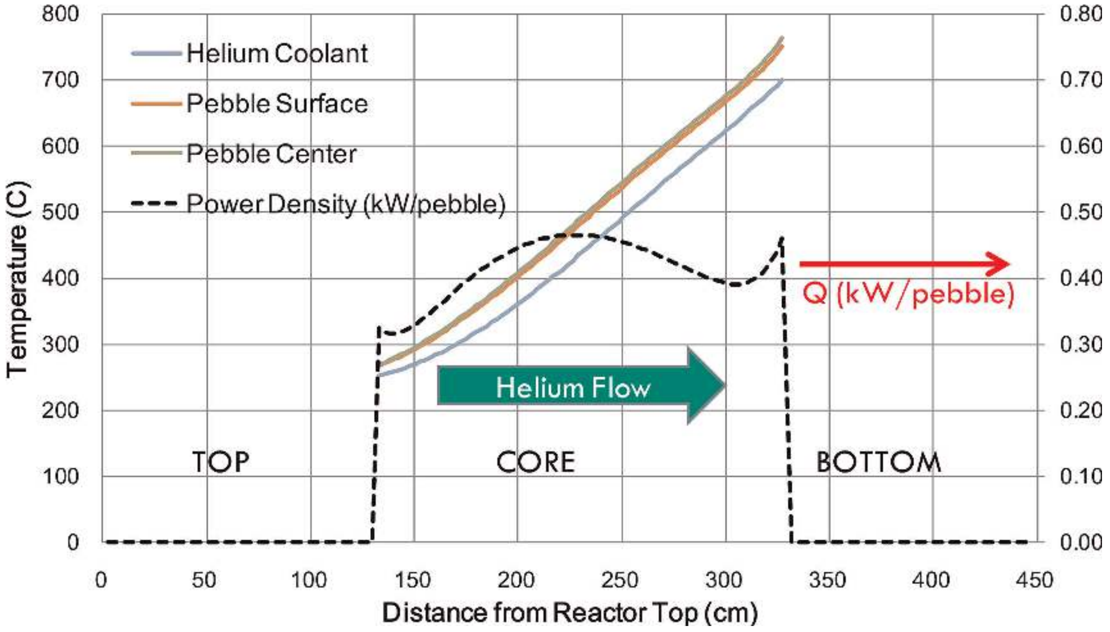

*Fig. 9. Thermal and flow analysis results*

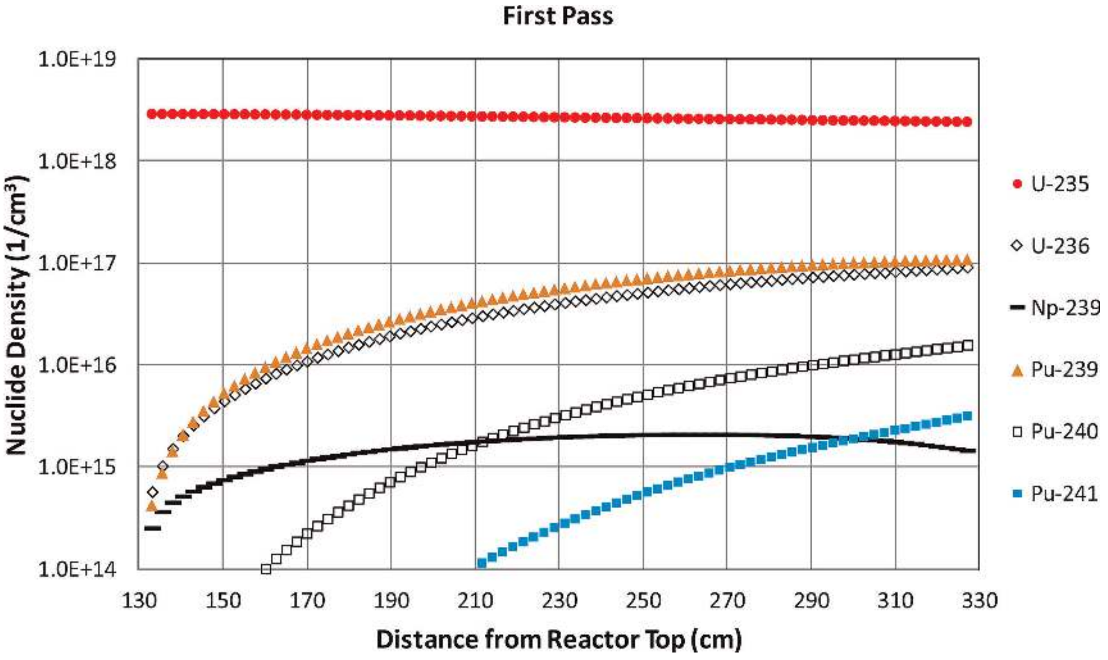

*Fig. 10. Nuclide density distributions after the first pass*

pebble, the maximum power density increases almost linearly with the HM loading. The trend can be explained from the fact that higher HM loading will result in a longer pebble fuel residence time and the axial power density profile will produce higher peak. Nevertheless, even for 10 g/pebble HM loading cases the maximum power density is still lower than 0.65 kW/pebble, that is one order smaller than the maximum allowable value.

Figure 5 shows the conversion ratio as a function of HM loading. As expected, lower uranium enrichment gives better conversion ratio. Higher HM loading per pebble also significantly increases the conversion ratio. With higher HM loading, the pebble fuel resides longer in the core and the fertile to fissile conversion is enhanced.

The in-core fissile inventory shown in Fig. 6 can be used to estimate the required amount of fissile inventory to start a reactor per GW thermal power unit. For the RDE considered here (thermal power of 10 MW) at the optimal HM loading, the required amount of fissile inventory ($^{235}$U) is around 80 kg.

For the optimal HM loading and uranium enrichment of 13 w/o, the axial and radial distributions of group neutron flux and power are shown in Figs. 7 and 8, respectively. From Fig. 7, it can be observed that axial power shows no strong

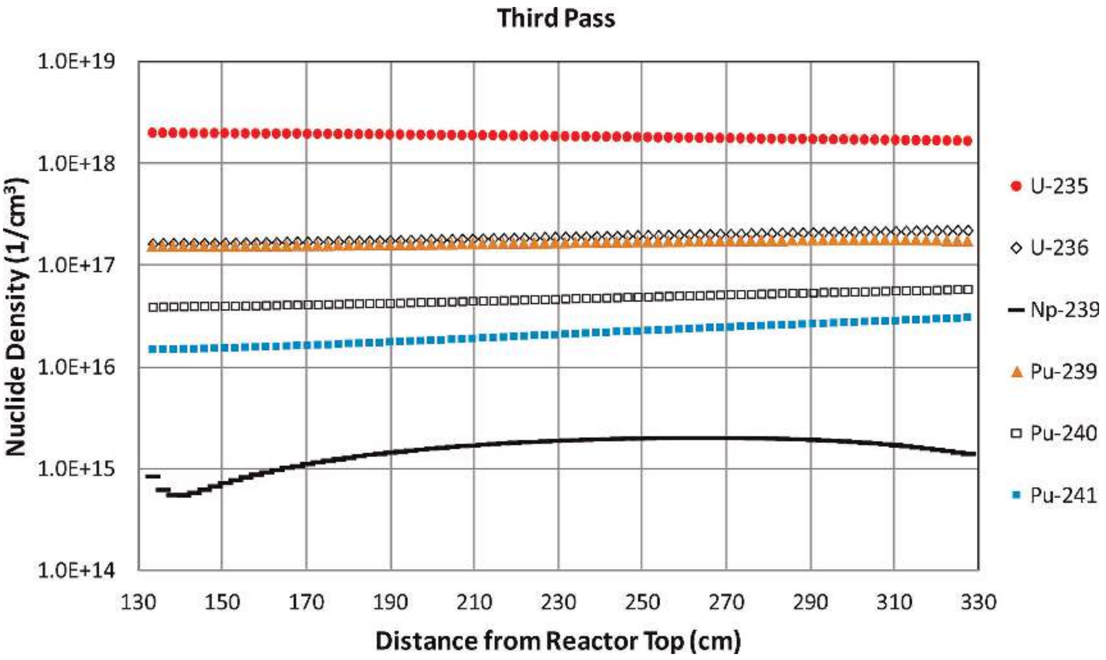

*Fig. 11. Nuclide density distributions after the third pass*

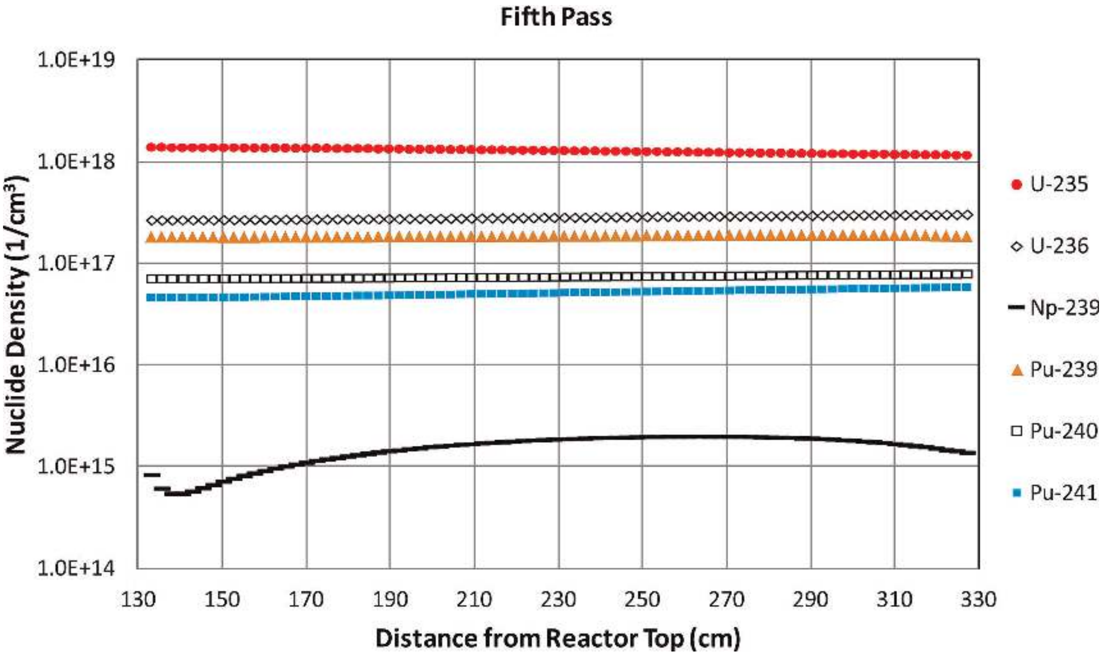

*Fig. 12. Nuclide density distributions after the fifth pass*

skewed profile which indicates that 5 passes are adequate for the present design. The thermal and flow analysis result is shown in Fig. 9. The maximum pebble fuel center temperature, as expected, appears at the bottom of the core but its value is lower than 800 °C.

Under the optimal HM loading and uranium enrichment of 13 w/o condition, the axial nuclide distributions of some important nuclides are shown in Figs. 10, 11 and 12 for the first pass, third pass and fifth pass, respectively. These nuclide densities are averaged by radial mesh volume. After the first pass, one can observe that fertile $^{238}$U is slowly converted to fertile $^{239}$Pu and $^{241}$Pu while the original fertile $^{235}$U is depleted slowly. After the third and fifth passes, the axial nuclide distributions show almost flatter profiles. The profile of the homogenized nuclide density for the 5 different passes (histories) is shown in Fig. 13. It can be observed that 5 passes for the present multipass scheme are adequate to obtain flat nuclide distributions, except for $^{239}$Np which is a short-lived nuclide. While a superior characteristic of the multipass scheme can be expected to boost the core burnup performance, the neutron loss in term of leakage is considerably high for this small core. The overall result is a rather poor neutron economic condition.

## 5 Concluding remarks and future works

A scoping study on the optimal fuel composition (heavy metal loading per pebble and uranium enrichment) for the 10 MWth RDE, with LEU $UO_2$ TRISO fuel under multipass fueling scheme, was conducted using BATAN-MPASS code. The objective function for the optimization is the fissile loading requirement per energy generated (kg/GWd). The optimal heavy metal loading was found around 8 g/pebble while the uranium enrichment corresponding to the 80 GWd/t discharge burnup constraint is approximately 13 w/o.

The results of the present scoping study can be improved in the future when other detail design parameters become available in the basic and detail design phases. These include the detail core-reflector structures and dimensions, control rod and reserved shutdown absorber in the radial reflectors, impurities in fuel and graphite etc. The results of safety evaluation in the future may provide feedback to the present scoping study and the optimal composition of the fuel slightly shifts from the above mentioned values.

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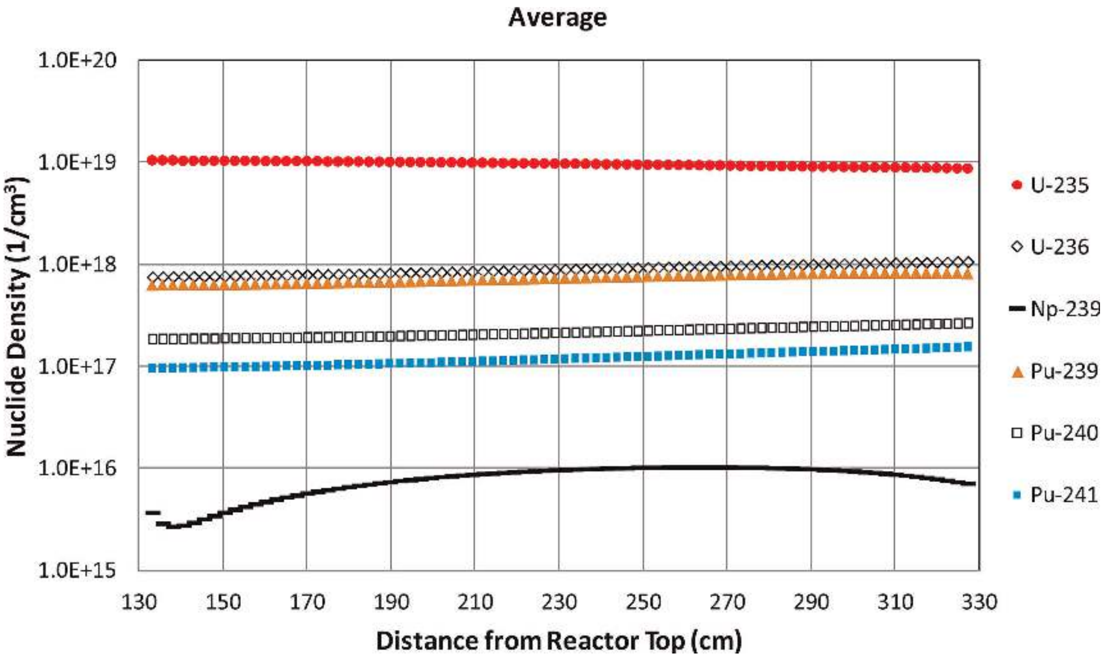

*Fig. 13. Nuclide density distributions of all passes (homogenized)*

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# Books · Bücher

**Safety of Research Reactors.** IAEA Safety Standards Series No. SSR-3, Published by the International Atomic Energy Agency 2016, ISBN 978-92-0-104816-5, 125 pp, 58.00 EUR.

The main objective of this Safety Requirements publication is to provide a basis for safety and for safety assessment for all stages in the lifetime of a research reactor by establishing requirements on aspects relating to regulatory supervision, management for safety, site evaluation, design, manufacture, construction, commissioning, operation, including utilization and modification, and planning for decommissioning.

Technical and administrative requirements for the safety of research reactors are established in accordance with this objective. This publication is intended for use by organizations involved in the design, manufacture, construction, operation, modification, maintenance and decommissioning of research reactors, in safety analysis, verification and review, and in the provision of technical support, as well as by regulatory bodies.

The safety requirements established in tins publication are applicable for the site evaluation, design, manufacture, construction, commissioning, operation, including utilization and modification, and decommissioning of research reactors, including critical assemblies and subcritical assemblies. The safety requirements established in this publication are also to be applied to existing research reactors to the extent practicable.

Research reactors with power levels in excess of several tens of megawatts, fast reactors and reactors using experimental devices such as high pressure and temperarme loops and cold or hot neutron sources may require the application of supplementary measures or even the application of requirements for power reactors and/or additional safety measures (e. g. in the case of reactors used for testing hazardous material). For such facilities, the requirements (and engineering standards) to be applied, the extent of then application and any additional safety measures that may need to be taken are required to be proposed by the operating organization and to be subject to approval by the regulatory body. Homogeneous reactors and accelerator driven systems are out of the scope of this publication.

All the requirements established here are to be applied unless it can be justified that, for a specific research reactor, critical assembly or subcritical assembly, the application of certain requirements may be graded. Each case in which the application of requirements is graded shall be identified, with account taken of the nature and possible magnitude of the hazards presented by the given facility and the activities conducted. Hereafter, subcritical assemblies will be mentioned separately only if a specific requirement is not relevant for or is applicable only to. subcritical assemblies. Paragraph 2.17 sets out factors to be considered in deciding whether the application of certain requirements established here may be graded.

This Safety Requirements publication follows the relationship between the safety objective and safety principles, and between requirements for nuclear safety functions and design criteria and operational criteria for safety. It consists of nine sections, two appendices and two annexes. Section 2 introduces the general safety objectives, concepts and principles for the safety of nuclear installations, with emphasis on the radiation safety and nuclear safety aspects of research reactors. Section 3, which draws on IAEA Safety Standards Series No. GSR Part 1 (Rev. 1). Governmental. Legal and Regulatory Framework for Safety deals with the general requirements on legal and regulatory infrastructure as far as these are relevant for research reactors. Section 4 deals with requirements on topics relating to the management and verification of safety. This section is based on IAEA Safety Standards Series No. GSR Part 2. Leadership and Management for Safety. Section 5 establishes requirements regarding the evaluation and selection of the research reactor site and deals with the evaluation of new sites and the sites of existing research reactor facilities. This section is based on IAEA Safety Standards Series No. NS-R-3 (Rev. 1). Site Evaluation for Nuclear Installations. Section 6 establishes requirements for the safe design of all types of research reactor, with account taken of the considerations mentioned in paras 1.8 and 1.9. Coherence is ensured with the Safety Requirements publication on the same subject for nuclear power plants. IAEA Safety Standards Series No. SSR-2/1 (Rev. 1). Safety of Nuclear Power Plants: Design, Section 7 establishes requirements for the safe operation of research reactors, including commissioning, maintenance, utilization and modification. Coherence is likewise ensured with the Safety Requirements publication on the same subject for nuclear power plants. IAEA Safety Standards Series No. SSR-2/2 (Rev. 1). Safety of Nuclear Power Plants: Commissioning and Operation. Section 8 establishes requirements for the preparation of the safe decommissioning of research reactors on the basis of IAEA Safety Standards Series No. GSR Part 6. Decommissioning of Facilities, while Section 9 establishes requirements for the interfaces between safety and security. Appendix I provides a list of the selected postulated initiating events to be considered in the safety analysis for a research reactor. Appendix II deals with the operational aspects warranting particular consideration. Annex I lists selected safety functions of the safety systems for research reactors and of other safety related items usually included in the design of research reactor. Annex II provides an overview of the application of the safety requirements to subcritical assemblies.