STATUS REPORT ON THE HFR CONVERSION AND RELICENSING PROJECT

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ABSTRACT

In 1999 the HFR license holder (JRC, Petten, the Netherlands) initiated a project to study the conversion of the HFR from HEU to LEU. The first phase of this project consisted of a parametric study to determine the optimum fuel element and control rod design within given boundary conditions such as geometry, density, performance and cycle length. Results of this study are a 22 plates fuel element (550 g ^{235}U) at a density of 4.8 g.cm^{-3} and a 17 plates control rod (440 g ^{235}U). The second phase contains all aspects related to the conversion including a full-scale test irradiation of a prototype LEU element. The actual conversion of the HFR requires a new license. For this reason the relicensing project has started in 2001. In this context many studies have been performed e.g. Risk Scoping Study, Safety Analyses, TOPA evaluation. The license application will be based on a new Safety Report and an Environmental Impact Statement and will be submitted to the competent Authorities at the end of October 2003.

1. Introduction

In 1999 the HFR license holder (JRC, Petten, the Netherlands) has started a project to review the possibility for conversion of the HFR from high enriched uranium (HEU) to low enriched uranium (LEU). With the conversion of the HFR a major contribution to the world wide non-proliferation of weapon grade material can be achieved since LEU at an enrichment below 20% is considered to be a non-weapon grade material.

The conversion of the HFR also enabled the import of HEU from the USA within the requirements of the Schumer-amendment during the course of the conversion project and during the actual transition phase from HEU to LEU. Furthermore the conversion of the reactor gave the opportunity for the HFR to participate in the return of spent HEU fuel assembles to the USA. Such a transport has taken place in the year 2001.
The conversion project is divided in 3 different subprojects i.e.:

- Phase 1: Feasibility study of the conversion;
- Phase 2: Technical qualification of the HFR conversion study;
- Phase 3: License application and amendment as a result of the conversion.

In the same period it was agreed with the competent Dutch authorities to perform a 10 yearly overall HFR safety re-evaluation and since the actual conversion requires a new license, it was decided to incorporate phase 3 of the conversion project in the HFR relicensing project.

Phase 2 of the conversion project contains 9 different activities related to the technical aspects while the HFR relicensing project has apart from the integrated conversion study 8 different activities.
In this status report an overview of the results and remaining actions are given. Also the time planning for the future license application is addressed.

2. Description of the HFR

The High Flux Reactor (HFR) Petten, the Netherlands, belonging to the Institute for Energy of the Joint Research Centre (JRC) of the European Commission is one of the most power full research reactors in the world. JRC as owner and license holder of the HFR is responsible for all activities related to the execution of European supplementary work.

Reactor operation, maintenance and commercial exploitation are subcontracted to the Nuclear Research and consultancy Group (NRG).
The HFR is a tank in pool type, light water cooled and moderated research reactor, operated at a nominal power of 45 MW. In operation since 1962 and following a complete gradual refurbishment over the recent years, the HFR provides a variety of irradiation positions:
- at central positions in the reactor core;
- in the reflector region and periphery of the core;
- pool side facilities for radioisotope production and material testing;
- horizontal beam tubes for fundamental and medical research including BNCT.

State of the art hot-cell laboratories on the NRG-site together with additional nuclear facilities such as the Low Flux Reactor and a Decontamination and Waste Treatment Facility, have lead to a unique HFR structure in which the NRG and JRC are actively cooperating with the aim to adopt a market oriented approach and to offer their longstanding and recognised competence to the medical, industrial and scientific world.
With at least 275 full power days per year and safe, reliable and predictable operation, the HFR is the major radioisotope supplier in Europe. Roughly 60% of the procedures within Europe makes use of the variety of radioisotopes produced at the HFR, leading to approximately 7 million treatments per year in Europe only.
The yearly operational programme is followed as closely as possible to offer the customers a predictable time table for experimental and isotope production planning.

3. Reactor core definitions

To perform the neutronic calculations, the need existed to specify the core loading as far as experimental utilisation is concerned. While in phase 1 of the conversion project only two simplified experimental loadings were needed, the detailed neutronic calculations of phase 2 showed the necessity to model a variety of experiments and radioisotope production rigs to the smallest detail. These different cores are identified as:
- *License core* in which the experimental facilities are all loaded with an Al-filler element in which an Al-insert is positioned. This core is considered to be the most reactive core and is used to review the license conditions related to reactivity effects (control rod worth, shut down margins, etc.);
- *Reference core* in which the experimental positions are loaded with a mixture of flux traps, Al-inserts and stainless steel absorbing experiments to stimulate an actual cycle core. This core is used to determine the critical rod position, cycle length and the progressive transition period.
- *Representative cycle core (RCC)* in which the experiment positions are loaded with a selection of experiments covering the wide range of utilisation/exploitation of the HFR. This core contains radioisotope production rigs including ^{99}Mo production rigs, stainless steel irradiations, (Cd-shielded) MOX/fuel pin irradiations and tritium breeding experiments. The RCC is used to determine the fluence rates and energy spectrum in the different irradiation facilities plus optimisation study of the reloading pattern.

4. Feasibility study of the conversion

4.1. General

The feasibility study had the objective to review the possibility of the conversion of the HFR within a set of boundary conditions. The work has been performed in close cooperation with the specialists of Argonne National Laboratory and included the following activities:
- construction of a detailed model of the HFR, the supporting structures and core components;
- calculation of the optimum fuel element and control rod design;
- first validation of the results.

Furthermore this activity included the investigation of the influence of different fuel element parameters (fuel, matrix, meat thickness, etc.) on the operation of the HFR. The set of boundary conditions comprised of:
- a gradual core conversion strategy thus giving a limited set of transition cores;
- an increase of fuel cycle duration from 24.7 to 28.0 full power days to improve flexibility of operation and core reloading;
- application of fully licensed and qualified fuel;
- minimal flux penalties while using a standard core reloading pattern;
- minimal changes of the fuel cycle costs.

4.2 Results

The results of phase 1 of the conversion project are:
- a detailed model of the HFR core and its supporting structure;
- an optimum fuel element design containing 550 g ^{235}U with the following characteristics:
  - fuel meat on basis of 4.8 g.cm^{-3} U_3Si_2-Al;
  - 20 fuel plates;
  - cladding thickness of 0.38 mm;
  - 40 Cd (∅0.5 mm) burnable poison wires embedded in grooves in the Al-side plates.
- an optimum control rod design containing 440 g ^{235}U with the following characteristics:
  - fuel meat on basis of 4.8 g.cm^{-3} U_3Si_2-Al;
  - 17 fuel plates;
  - cladding thickness of 0.38 mm;
  - standard Cd absorber sections.

5. Technical qualification

5.1. General

The outcome of phase 1 of the conversion i.e. the detailed fuel element and control rod design as well as the model of the HFR and its surrounding structure serve as input for phase 2 of the conversion study “Technical qualification of the conversion”.

Due to the complexity of phase 2 and the variety of the aspects to be covered within this technical qualification, it was agreed to divide phase 2 in 9 different activities:
1. Neutronic calculations;
2. Review of hydraulic pressure drop;
3. Thermal hydraulic calculations;
4. Literature study;
5. Mechanical consequences of the conversion;
6. Consequences on the experiment behaviour;
7. Consequences on the fuel cycle;
8. Consequences on the incident/accident calculations;
9. In-pile testing of a LEU prototype fuel element.

The calculational results and theoretical considerations per activity are used in the course of the HFR relicensing project with emphasis on the Safety Analysis Report and the Environmental Impact Statement.

5.2 Neutronic calculations

The HEU/LEU-transition period will be limited as much as possible. A standard HFR refuelling pattern (5 fuel elements and 1 control rod per cycle) will be applied leading to a fully LEU loaded core after 7 transition cycles.

Following the successful execution of these calculations the calculation of the transition period could start. The fuel distribution in the core is calculated by the REBUS code for the reference core. This way a cycle by cycle burn-up and the shift from HEU to LEU was determined. In contrary to present operational procedures the LEU fuel elements during the transition period will not have an intermediate cooling period. Furthermore using the generated data on the fuel distribution the following license conditions were reviewed on basis of the license core (Al-plugs):

- excess reactivity at BOC, EOC and equilibrium conditions;
- subcriticality when all rods are set at half of their reactivity worth;
- subcriticality when 2 most reactive rods are fully withdrawn.

The calculations show that after a transition period from 7 to 8 cycles the equilibrium HEU core is transferred into an equilibrium LEU core and that the current license conditions are not jeopardised during the transition period.

5.3 Review of hydraulic pressure drop

At the HFR a hydraulic test loop is available to test the hydraulic characteristics of in-core components prior to their positioning in the HFR. The facility has been used for decades to determine the hydraulic resistance of different fuel element designs, Be- filler elements and in-core mock-ups. Upon arrival, a dummy (inert) and a LEU prototype fuel element were tested while the results were compared with the characteristics of a standard HEU fuel element. Furthermore the historical data of previous measurements in the framework of the RERTR programme and Petten site fuel developments' projects were used for comparison.
The measurements show that only minor differences between the flow rates in LEU and HEU fuel elements at the HFR core pressure difference (1.1 bars) occur.

5.4 Thermal hydraulic calculations

To prevent occurrence of any fuel plate damage during normal operation the so-called "Bubble Detachment Criterion (BDC)" is applied. By using this criterion for each reactor cycle the maximum allowable inlet temperature is calculated at the location of the core hot spot i.e. any position (fuel plate and Z-axis) in any fuel element giving the highest fuel plate surface heat. On basis of the outcome of the neutronic calculations the highest loaded fuel element was transferred into a RELAP5-model. The standard HFR conditions (pressure, flux profile) and the data deriving from the hydraulic measurements were applied to determine the allowable inlet temperature for this specific case.
The results show that only a minor acceptable decrease in allowable inlet temperature will occur which is merely caused by the more profound flux peaking.

5.5 Literature study

The bibliography or literature study comprises of the background information of research reactors, the objectives of conversion study, fuel development programmes, the Reduced Enrichment for Research and Test Reactors programme (RERTR) and the Research Reactor Fuel Management meeting (RRFM). It also addresses fuel testing of the HFR within the RERTR-programme as well as other (commercial) irradiation programmes. In can be concluded that previous work performed both at Oakridge Research Reactor and the HFR forms a sound basis for the present conversion of the HFR with U_3Si_2-Al fuel at a uranium density of 4.8 $g.cm^{-3}$.

5.6 Mechanical consequences

Two differences between the HEU and LEU control rods exist i.e. the weight of the rods and the number of fuel plates. These differences will influence the control rod drop time. Furthermore the increased weight of the fuel element will change the mechanical stresses in the lower grid.

Analysis of stresses in the lower grid

The worst case scenario to determine the influence of the conversion on the mechanical stresses of the lower grid is defined by:

- all experimental positions loaded with Al-fillers containing Al-inserts (increased gravity load);
- maximum primary flow thus increasing the dynamic load of the coolant;
- the primary temperature difference (≈ 10ºC) imposed on the grid to ensure a maximum thermal stress.

In reality this combination of parameters will never occur but the detailed analysis show that only marginal differences in mechanical stresses in the full LEU versus full HEU core will be present.

Earthquake analysis

To determine the behaviour of the HFR reactor vessel and its internals during a postulated earthquake, it was decided to include an earthquake analysis in phase 2 of the conversion project. So far a FEM-model of the HFR with its surrounding structures and all internals (guide plate, grid block and gridbars) has been prepared and the calculations for different seismic loads are ongoing.

Control rod drop times

The control rod droptime is influenced by several parameters such as gravity, mechanical friction and hydraulic resistance. Due to the conversion the number of plates and the weight of the rod will change while the outer shape of the rod and the drive mechanism remain unchanged.

On basis of 10 years experience with measured rod drop times, a computational model to predict the influence of the conversion has been set up. The model uses two definitions of the rod drop time:

- full primary flow (4000 $m^3.h^{-1}$) and rods fully withdrawn (0.75 m);
- decay heat removal flow (300 $m^3.h^{-1}$) and rods set a subcritical position.

The results indicate that the HFR conversion hardly influences the values of the control rods drop time.

5.7 Consequences on the experiment behaviour

Standard reloading pattern

The results of the neutronic calculations with respect to the transition period and license related requirements have been discussed in 5.2 “Neutronic calculations”. While these calculations have been performed based on a standard reloading pattern in the reference core, a separate activity concerns the influence of the conversion on the fluence rates and nuclear heating in the experimental devices and the radioisotope production rigs. For the first phase of these calculations, the simplified HFR-model (no supporting structure nor beamtubes) loaded with the set of experiments as defined in the RCC were applied. The objective was to investigate the influence of the experiments in a global way without investigating the detailed behaviour within the sample volumes or irradiation targets. The results show a substantial decrease in especially the thermal fluence rates in the west side of the core.

Feedback of users

The results of these calculations were reported to the HFR users community and their feedback and requirements for additional calculations were analysed. On basis of these requirements a second set of calculations was performed using the full scale model and experiment specific tallies. The objective of this second set of calculations was to provide experiment specific data on spectrum shift and energy dependent fluence rates within sample volumes or irradiation targets. These calculations confirm the global calculational results.

Also a set of calculations to determine the influence of the conversion on the nuclear heating in the RCC was performed. The results show that the conversion only gives a minor decrease of the nuclear heating in the experimental positions while due to the high ^{238}U content in the fuel assemblies the nuclear heating in the fuel positions increases significantly.

Core optimisation
In the west side of the core normally the irradiation rigs needing the highest thermal fluence rates (radioisotope rigs) are positioned. The conversion using a standard fuel reloading pattern resulted in a decrease of 10% to 15%. It was therefor decided to perform a core optimisation study with the objective to restore the thermal fluence rates in the west side of the core (e.g. PSF-west, C-, D-, and E-row). The starting point of this optimisation is an earlier path finder study performed by ANL and presented at the 2000 RERTR conference (Las Vegas, USA). During the execution of the calculations different loading strategies were applied. The analysis shows that this alternative fuel reloading pattern will lead to thermal fluence rates which are advantageous for radioisotopes production while the decrease in the east side of the core are still acceptable for the scientific applications.

5.8 Consequences on the fuel cycle

Cycle duration
One of the boundary conditions of the conversion project was to optimise fuel consumption as a function of cycle length. As a consequence it has been decided to include an option to increase the cycle length to 28 full power days. With this increased cycle length it will be possible to remain at the present full power days per year (275 fpd) while reducing the number of cycles from 11 to 10 per year, thereby reducing front end and back end fuel cycle costs.

Fresh fuel element storage/ critically aspects
The HFR fuel elements and control rods are stored in dedicated and secured vaults. The consequences of the conversion i.e. storage of LEU instead of HEU elements have been analysed during normal and accident conditions. The results show that K_{eff} always remains far below the acceptance limit of 0.915.

Spent fuel element storage/critically aspects
Also the spent fuel elements and control rods are stored in dedicated storage racks in the HFR pools. The criticality analysis of the accident condition results in a K_{eff} value which is far below the acceptance limit of 0.915.

5.9 Consequences on the incident/accident calculations

Technical safety specification
The existing HFR Technical Safety Specifications (TSS) are based on the HEU fuelled core and have been translated in English to ease the discussion with subcontractors and ANL. Each individual condition of these TSS was then reviewed on the consequence of the conversion on the license condition. In general it can be concluded that hardly any license condition that is not depending on the fuel properties is influenced by the conversion. Within the HFR license renewal a revised set of Technical Safety Specifications will be prepared on basis of the outcome of the different relicensing activities.

Core nuclide inventory
A second activity of the incident/accident calculations concerns the renewed nuclide inventory after the gradual core conversion. The calculations were performed on basis of the worst case scenario i.e.:
- equilibrium LEU loading;
- each fuel section containing the maximum ^{235}U amount (550 or 440 g ^{235}U + 2%);
- reactor power set at 50MW continuously.

5.10 Irradiation of prototype LEU fuel element

Phase 2 of the conversion project also includes the in-pile testing of a full scale prototype LEU fuel element. Since the type of fuel and the fuel element design are well known from earlier fuel test irradiations in the framework of the RERTR programme, no post irradiation examination will be performed. After the hydraulic testing of the fuel element it was loaded in the core for additional reactivity measurements and it was also positioned in the license core of the annual flux measurement programme by which the reactor power distribution is monitored.
In contrary to earlier test irradiation, the prototype fuel element will completely follow the standard HEU reloading pattern without intermediate cooling periods. The irradiation commenced at reactor cycle 2003-02 and was originally scheduled to end after cycle 2003-09 to achieve an averaged burn-up of 50%. During cycle shut down periods coolant gap measurements are performed using go/no go gauges. As expected no irregularities have been found.
In order to obtain increased fuel cycle flexibility in the future it has been decided to continue the current irradiation in unoccupied irradiation positions until a burn-up of 75% is reached.

6. HFR license renewal

6.1 General
While the work related to the conversion was ongoing, the HFR license holder together with the Dutch competent authorities launched a project for the renewal of the HFR license on basis of the “state of the art” (inter)national criteria and guidelines. Apart from the activities of the conversion project this license renewal consists of the following activities:
- Risk Scope Study;
- Safety Analysis;
- Review of Ageing Criteria;
- Analysis of external events (fire, floading and seismic);
- Safety Evaluation;
- Safety Concept;
- Modification Program;
- Safety Report;
- Environmental Impact Statement.

In the following paragraphs each aspect is briefly addressed.

6.2 Risk Scope Study
The Risk Scope Study (RSS) represents a limited Probabilistic Safety Analysis and is split-up in 3 different stages as prescribed by the IAEA guidelines:
- level I: Review of accident scenario’s to determine core damage frequency;
- level II: Failure probability of the containment to determine releases;
- level III: Consequences of the possible releases to the environment.

RSS phase 1 was reviewed and accepted by an IPSART-mission of the IAEA leading to the start of the level 2 calculations. A second IPSART mission looked at the PSA level 2 and level 3. The comments received are currently being worked out. Analyses for both LEU within the current installation and the LEU case after modification of the installation coming out of the relicensing project have been implemented. The Core Damage Frequency (CDF) reduced from 5.10^{-5} to 1.10^{-6} per year. HFR compares to CDF as results obtained for modern Nuclear Power Plants.

6.3 Safety Analysis

On basis of IAEA-SS45 a set of enveloping postulated initiated events ("PIE's") was established containing all possible failure scenario's which could occur at the HFR. Typical examples of these thermal hydraulic PIE's are:

- loss of off-site power;
- criticality during fuel handling;
- start-up accident and control rod drive/system failure;
- unbalanced rod position;
- fuel channel blockage;
- primary coolant boundary rupture ("LOCA's").

It should be mentioned that within the group of "primary coolant boundary rupture" also the so called large break LOCA is included.

Apart from the thermal hydraulic analyses listed above also a set of radiological PIE's is being reviewed:

- failure of the experimental devices;
- pool damage due to container drop;
- effects of the primary coolant boundary rupture.

Also the plant response as a result of postulated external events (fire, flooding and earth quakes) is being investigated.

All thermal hydraulic analyses have been submitted to the Dutch authorities and approved by their external consultant.

6.4 Review of Ageing Criteria

The basis of the ageing evaluation are IAEA TECDOC-792 "Management of research reactor ageing" as well as the applicable guidelines for NPP's. Three different ageing studies are performed:

- electrical components (cabling, wires and connectors);
- civil structures and buildings;
- mechanical systems, structures and components.

Review of the ageing aspects is performed to determine the reliability of the different systems to fulfil their tasks in the three basis functions i.e. reactor shut down, removal of residual heat and confinement of radioactivity. While the review of the electrical ageing has been accepted by the competent authorities, the other two ageing studies are near to completion.

6.5 Safety Evaluation

On basis of the state of the art (inter)national guidelines and requirements the HFR was reviewed on so called TOPA aspects covering the complete scale of activities related to the operation of a high power research reactor. The TOPA-review covers all aspects related to Technical, Operational, Personnel and Administrative requirements and revealed several deficiencies (including recommendations) and suggestions for improvement. The majority of the deficiencies is related to the particular situation between license holder and operator, historical aspects and changes in license requirements. The reports have been accepted by the Dutch authorities and deficiencies are steadily being handled.

6.6 Safety Concept and Modification Program

The safety concept of the HFR must fulfil the three functions of safety i.e. shutdown of the facility, longterm removal of decay heat and containment function and is based on the principles of defence in depth and multiple safety barriers for all accident conditions. Furthermore a 30 minutes autarchy time has been introduced during which period no credit for operator's intervention during accidents is taken. The analyses of all possible events including the LB-LOCA have resulted in a number of possible improvements which are implemented in the modification program.

The major items of the modification program are:

- introduction of additional vacuum breakers on the primary system;
- accident pressure equalisation lines;
- controlled use of pool water;
- replacement of diesel driven decay heat removal pump by divers electrical pump;
- interlock modification by loss of off-site power;
- limitation on the portal crane movement.

6.7 Safety Report

As part of the license application a safety report is being prepared. The content of the safety report, format and level of details follow the requirements given in the IAEA Safety Series No. 35-G1. The experiences gained during the relicensing of the HOR-research reactor (Delft, the Netherlands) and power plants in the Netherlands are used in preparing the different chapters in the report.

According to the Dutch legislation a safety report must include:

- a description of the plant and its specific application;
- a description of the measures taken to prevent damage or to reduce the risk of damage during normal operation and postulated initiating events;
- a risk analysis of damage outside the facility caused by these events.

6.8 Environmental Impact Statement

The Environmental Impact Statement (EIS) covers all aspects related to nuclear safety, conventional safety, effluents, utilisation, etc. as laid down in the Dutch laws. It should also address the influence of the modification (i.e. conversion from HEU to LEU) and foreseen technical modification resulting from the TOPA and PIE-analysis. The report has been set up on basis of existing knowledge of NPP's and is prepared in close cooperation with representatives of different Ministries.

7. License application

According to the Dutch laws the license application will be based on two main set of documents i.e. the HFR Safety Report and the Environmental Impact Statement. The other documents such as a detailed description of the plant, the technical aspects of the conversion study and the analysis of the thermal hydraulic and radiological postulated initiated events are underlying documents which are not part of the license application.

The license application will be submitted to the competent authorities in the last quarter of this year. Within the license application also a transfer of license holder from JRC to NRG is foreseen. While NRG will become the new license holder, JRC will remain the owner of the HFR. A new license is expected to be granted in the second half of 2004. The execution of the modification program will be performed in 2004/2005. The actual conversion of the HFR will take place in 2006.

8. Conclusions

Most of the activities which have to be performed in the framework of the conversion of the HFR from HEU to LEU fuel have been completed or will be completed in the near future. A request for a renewed license will be made this year and is expected to be granted in the second half of this year. A modification program will be set up to further improve the safety level of the HFR.

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