RERTR 2010 — 32nd INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 10-14, 2010
SANA Lisboa Hotel
Lisbon, Portugal

SAFETY ASPECTS OF RESEARCH REACTOR CORE MODIFICATION FOR FISSION MOLYBDENUM-99 PRODUCTION

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ABSTRACT

Installation of irradiation boxes in research reactor core to irradiate Low Enriched Uranium (LEU) plates for fission ^{99}Mo production is one of the experiments involve important safety aspects and considerations. More specifically, safety aspects of this core modification include qualification of LEU plates to be irradiated, core nuclear and thermal-hydraulic design in steady state conditions and safety analysis, review and authorization, commissioning, and licensing process. The present paper discusses the safety aspects and considerations of this type of modification of Egypt Second Research Reactor (ETRR-2) core on the basis of the IAEA safety requirements for research reactors. The commissioning tests of the modified core and updating of licensing documents, in particular the Safety Analysis Report (SAR), the Operational Limits and Conditions (OLCs), and the procedures for operation and emergencies, are also discussed.

1. Introduction

ETRR-2 is an open pool type, 22 MW power, cooled and moderated by light water, and reflected by beryllium reflectors. Its core is a fixable arrangement up to 30 fuel elements of 19.7 % enrichment MTR type. The reactor went first criticality on November 1997 and was operated with 29 fuel elements and Co irradiation device (CID) for ^{60}Co production. On 28 October 2009, the reactor core was modified to irradiate LEU plates in two irradiation boxes for the purpose of fission ^{99} Mo production.

LEU plates will be irradiated in special dedicated irradiation boxes to produce 1000 Ci of ^{99} Mo per week. The existing CID will remain in the new core design. As shown in Fig. 1, two fuel elements were replaced with two irradiation boxes Mo1 and Mo2 placed inside the modified core. Each irradiation box contains two plate holders where the LEU plates are loaded as shown in Fig. 2. The irradiation boxes will be loaded into or removed from the core while the reactor is shutdown.

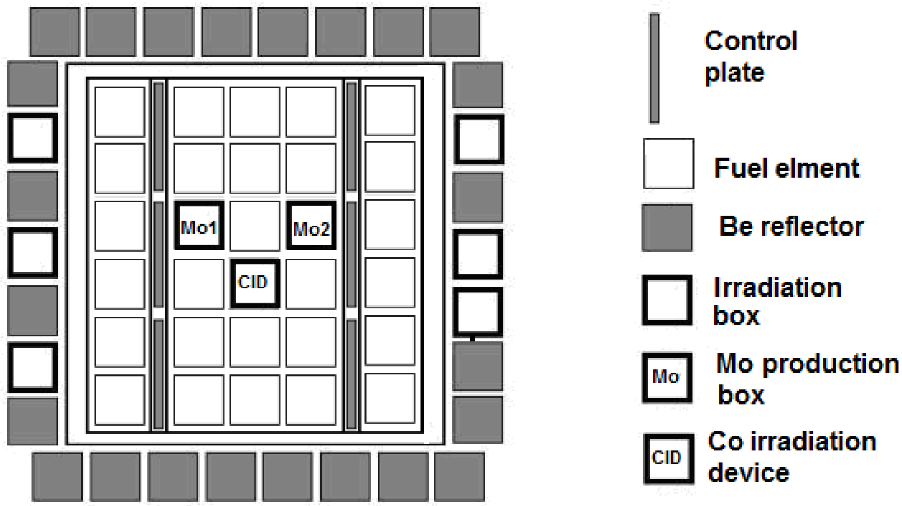

Figure 1: ETRR-2 modified core

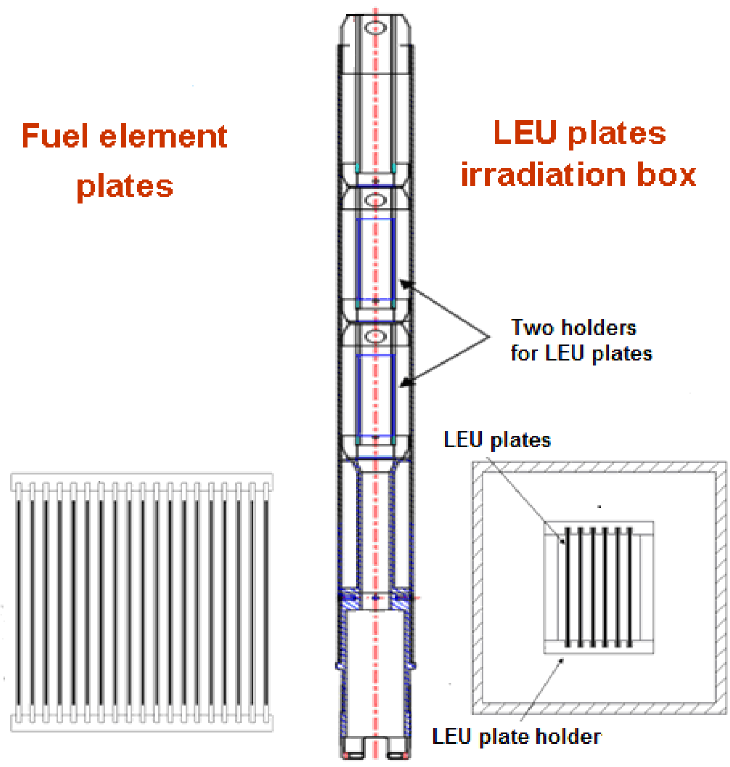

Figure 2: Cross section view of fuel element and irradiation box at plates zone

Important safety aspects should be considered in the implementation of this core modification. These aspects include the qualification of the LEU plates to be irradiated, core detailed analysis (nuclear and thermal-hydraulic design and safety analysis), commissioning, and licensing process. A detailed core analysis demonstrating the safe implementation of ^{99}Mo production experiment should be performed including assessment of the core fuel elements and irradiation of the LEU plates in the new core configuration. The installation and commissioning of ETRR-2 core modification requires authorization from the regulatory body [1, 2]. In the present paper, the safety aspects and considerations when implementing ETRR-2 core modification project have been discussed on the basis of the IAEA Safety Standards [1, 2, 3, 4, 5].

2. Qualification of LEU plates

ETRR-2 core modification involves irradiation of LEU plates for fission ^{99}Mo production. A LEU plate has to be qualified by irradiation tests simulating the intended operating conditions. These qualification tests are aimed at demonstrating that the design limits are not exceeded during steady state and transient conditions. The analysis of the results of the qualification tests allows the determination of the plate utilization limits.

The previous experience in the qualification of similar type of LEU plates which are irradiated in the Argentinean Reactor RA-3 has been considered. Irradiation and processing of these plates for production of radioisotopes have not shown any failures during nuclear handling. The design and manufacturing of these plates are similar to the plates for ETRR-2 reactor.

3. Core analysis

3.1 Nuclear design

The primary objective of the modified core nuclear design and management analysis is the verification of safe operational conditions [3, 5]. All the parameters required to verify accomplishment of the design limits should be calculated. The shutdown margin of the First Shutdown System (FSS) and Second Shutdown System (SSS), the control rod worth and the core excess reactivity, the worth of the experiments, end of cycle reactivity needed for control, and maximum discharge burn up have been calculated [3]. The values of these parameters should be within the limiting conditions specified in the OLCs for safe operation. The nuclear design demonstrates that the values of these parameters for the intermediated and equilibrium cores are kept within the reactivity limits specified in the OLCs. Acceptance values (in pcm) are summarized in Table 1. The maximum discharge burn up of the modified core is less than that of the 29 fuel elements core.

A detailed power distribution across the reactor core should be calculated verifying that the nuclear Power Peak Factor (PPF) remains below the value specified in the OLCs (PPF < 3). This parameter is used as an input to the steady state thermal-hydraulic calculations and safety analysis. Nuclear design has shown that replacement of two fuel elements with two Mo production boxes would have a PPF factor less than 2.5. Also, changes to the reactivity feed back coefficients and kinetic parameters which are used in the analysis of reactivity insertion accident, have been calculated. It is shown that no changes to kinetic parameters for the 27 fuel elements configuration.

Table 1: Limits of nuclear design parameters

Parameter	Acceptance value
Shutdown Margin (SM) of FSS	≥ 3000
SM of FSS with single failure	≥ 1000
Reactivity Safety Factor (RSF) (RSF = total control rods worth / core excess reactivity)	≥ 1.5
SM of SSS	> 1000
SM of SSS with single failure	> 500
The maximum allowed reactivity for any fixed experiment	≤ 1200
The maximum allowed reactivity for all experiments	≤ 3000
End of cycle reactivity	≥ 1000

A secondary objective of nuclear design is to meet utilization requirements:

- The two irradiation boxes are placed in high flux positions about 2.0×10^{14} n/cm^2.s;
- The design has been performed for 24 LEU plates which cover possible increase of ^{99}Mo production capacity ;
- Operation cycle length of intermediated and equilibrium cores is multiple of irradiation time of 5 days at full power (i.e. 5, 10, 15, or 20 days), so that ^{99}Mo production is on fixed days of the week .

3.2 Thermal-hydraulic design

The objective of the thermal-hydraulic design is to ensure adequate cooling of core fuel elements and LEU plates, so that the fuel and clad temperatures are kept within acceptable values in forced and natural operational states [3]. Aadequate cooling of aluminium clad fuel is that the clad temperature is kept below 105 ^{o}C [6]. The cooling design of LEU plates was performed to ensure that there is no boiling in the coolant channel in nominal power conditions. ETRR-2 steady state operational states are (1) forced convection in which the reactor is operated at 22 MW with operation of two core cooling pumps (1950 m^3/hr) or operated at 11 MW with one core cooling pump and (2) natural convection and a total core power of 400 kW. This design should demonstrate that the reactor can be operated with enough safety margins against the thermal-hydraulic critical phenomena in forced and natural operational states [3]. The critical phenomena that are of concern in the thermal-hydraulic design are flow Redistribution (RD) and Departure from Nucleate Boiling (DNB) [7]. Onset of Nucleate Boiling (ONB) is also considered in the design as a measure of the approach to a heat transfer crisis. The coolant velocity between two plates should be below the critical velocity.

Uncertainties due to fuel fabrication tolerances, deviations in the construction process, simplifications made in the models, and possible deviations in the operational conditions should be specified in the thermal-hydraulic design [3]. The calculations have been performed for the hot channels of fuel elements and LEU plates in Mo box. The same uncertainties as for the fuel elements calculations were adopted for the LEU plates. Limits of design parameters are summarized in Table 2 where the ratio is between the heat flux leading to phenomena and the local heat flux in the plate. The thermal-hydraulic design of the modified core demonstrates that the values of these parameters are kept within these design limits.

Table 2: Limits of thermal-hydraulic design parameters

Parameter	Acceptance value	
	Core fuel	LEU plates
Maximum clad temperature	≤ 105 ^{o}C [(a)]	< boiling temperature
ONB ratio	≥ 1.3	NA
RD ratio	≥ 2.0	
Minimum DNB ratio	≥ 2.0	
Maximum velocity ratio (max. coolant velocity/ critical velocity)	≤ 2/3	

[(a)]Without considering uncertainties
NA: Not applicable

The computer codes used for the calculations should be qualified and valid to use in research reactor design. Validation and verification of the used codes (TERMIC, CONVEC, and CAUDVAP) show that these codes are appropriate and simple tool for thermal-hydraulic design purposes of research reactor cores [8]. Mock up and practical tests of Mo production box allow for an experimental validation for the hydraulic calculations [9].

The results of thermal-hydraulic design are the basis for specifying the safety limits in OLCs applicable to the forced and natural operational states and safety system settings of reactor power, coolant flow rate, core pressure drop, and coolant temperature at the core outlet (or inlet). The previous design was done for the minimum core configuration of 24 fuel elements and water boxes. It is applicable to core configurations having between 24 and 30 fuel elements and cores having 29 fuel elements and CID. This design shows that the specified safety limits are applicable to the modified core.

3.3 Safety analysis

Analysis of Postulated Initiating Events (PIEs) originally performed for 29 fuel element core has been revised due to changing number of fuel elements and installation of Mo production box. The revised analysis should include initiating events arising from the utilization of the ETRR-2 to produce ^{99}Mo from fission of uranium plates. In the preparation of the set of PIEs for the analysis, the selected PIEs in the Appendix of Safety Series No. 35-S1 is considered [3]. PIEs of the new ETRR-2 configuration are: (1) Loss of flow, (2) Insertion of excess reactivity (3) Coolant channel blockage, (4) Loss of coolant, (5) Loss of heat sink, and (6) Erroneous handling of irradiated plates and fall of Mo production box.

Mainly, the safety analysis is to enable the operator to understand the basis for the safe operation of the reactor and to demonstrate that the design and the related operational procedures will contribute to the prevention and mitigation of accidents. The safety analysis should identify the design basis accidents. In addition, accidents beyond the design basis accident may be analyzed for purposes of emergency planning and accident management [3]. Design Basis Accidents of the new ETRR-2 core have been identified and analyzed. It has been shown that no damage is produced to the fuel elements or LEU plates due to the timely and effective actuation of the reactor protection system, safety systems and engineered safety features provided in the ETRR-2. Also, some beyond design basis accidents have been identified and qualitatively analyzed.

4. Commissioning

ETRR-2 core modification to irradiated LEU plates for ^{99}Mo production is a project with major safety significance. The IAEA Safety Standards require implementation of a commissioning programme for this category of research reactor modification [1, 3].

The commissioning programme for in ETRR-2 core irradiation of LEU plates for ^{99}Mo production covers the following:

- Description of the commissioning organization for the project as well as the roles and responsibilities of the individuals involved;
- The commissioning activates (core modification including refueling and replacement of two fuel elements with ^{99}Mo production boxes, pre-operational tests, approach to criticality and low power tests with dummy plate and with LEU plated, power rise tests, and irradiation of LEU plates at half power and full power);
- ETRR-2 Safety Committee review and assessment of the safety during the commissioning
- Commissioning test procedures;
- Quality management for commissioning that includes verification, review, audits, and treatment of non-conformances.

The commissioning tests for the modified core include:

- Hydraulic test of core cooling verifying that the core cooling conditions remain within acceptable criteria where Mo production boxes are in place inside the core;
- Approach to criticality with and without Mo production boxes and measurements of reactivity worth of the Mo production boxes;
- Measurements of the SM, reactivity worth of the control rods, and core excess reactivity;
- Flux measurements and estimation of power peaking factors;
- Measurements of flux in LEU plates and validation of nuclear heating calculation;
- CICs (Compensated Ionization Chambers) calibration and adjustment of the safety system settings, based on thermal methods;
- Verification of tools and equipment for handling the new irradiation box and loading/unloading of LEU plates.

The results of the commissioning tests demonstrate that the design intent is met for the modified core (see Table 3). CICs have been calibrated against thermal power measurements during power rise procedure ensuring linearity and provide an accurate relationship between indicated and actual core power.

Table 3: Acceptance value of the measured parameters

Parameter	Acceptance value
Core pressure drop (dp) for hydraulic verification of cooling system	New core dp > dp of 29 fuel elements core
SM of FSS	Table 1
SM of FSS with single failure	
Reactivity Safety Factor	
The reactivity worth for any Mo Box	
The maximum allowed reactivity for all experiment (two Mo boxes + CID)	≤ 3000
PPF	< 3

5. Licensing process

The IAEA Safety Standards require that projects with major safety significance to be authorized from the regulatory body prior to its implementation [1, 2].The detailed engineering of the modifications, the revised safety analysis, and the commissioning tests procedures have been submitted to the regulatory body in application for loading and commissioning authorization of the new core. In application for operation license for irradiation of LEU plates, the ETRR-2 operating organization should submit updated safety documents to the regulatory body:

- Updated SAR with the results of the commissioning;
- Updated OLCs:
- Emergency procedures;
- Updated Operation Manual (OM) and training evaluation.

Specifically, the ETRR-2 SAR follows the appendix "contents of a Safety Analysis Report" [3]. The updated SAR is following previous format and index with updating the chapters of the reactor description, design, core, utilization, and safety analysis. OLCs shall be presented in a separate document. Updating emergency procedures is to cope with erroneous handling and transfer of irradiated plates. An OM dedicated for loading / unloading of the plates in the Mo box, irradiation, handling, and loading in shielded container has been prepared.

6. Conclusions

ETRR-2 core modification to irradiate LEU plates for ^{99}Mo production is a project with major safety significance. A detailed safety analysis of the modified core has been performed to demonstrate that the reactor can be kept within the safety conditions established in the design. A commissioning program has been established to verify that the reactor can be operated according to the design intent and in compliance with the OLCs. Updated safety documents (SAR, OLCs, emergency procedures, and OM) are the basis for the licensing process of the modified core.

It can conclude that ETRR-2 core modification for ^{99}Mo production follows the IAEA Safety Standards requirements for projects with major safety significance.

7. References

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