RERTR 2011 — 33rd INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 23-27, 2011
Marriott Santiago Hotel
Santiago, Chile

Core Performance Improvement Using U3Si2-Al Fuel in the RP-10 Modernization

Eduardo Anibal Villarino
Nuclear Engineering Department
INVAP SE, Cmdte Luis Piedra Buena 4950 - Bariloche – Argentina

and

Alberto Gallardo Padilla
División de Reactores Nucleares
IPEN, Av. Canadá 1470 – San Borja – Lima– Perú

ABSTRACT

This paper presents the design of a new RP-10 core using U3Si2-Al fuel assembly. This work is supported by the IAEA CSA PER/4023/10/01 "Modernizing and Improving the Utilization of the RP10 reactor". The main objectives of this modernization are to improve the fuel economy and the utilization of the reactor.

The design of the Fuel Assembly was done following the criteria to minimize the perturbation in the current reactor design and the design of the new core was done following all the current nuclear safety criteria and the new utilization requirements, like a new facility for the Mo99 production by fission.

The U3Si2-Al FA and the new equilibrium core fulfill all the design criteria. The main characteristics of the FA and core, and their main neutronic parameters are presented. A comparison with the current U3O8-Al core and the improvements regarding to the fuel economy and irradiation capabilities are also given.

1. Introduction

The RP-10 [1] is MTR pool-type reactor, with a thermal power of 10 MW, generated in U3O8 plates 19.75% U-235 enriched, it became critical in 1989 and it is used for research in reactor physics and for radioisotope production. It has five control fork type rods, made of cadmium, silver and Indium alloy. The core, surrounded by graphite and beryllium neutron reflectors, is at the bottom of a 4m diameter and 11m deep cylindrical tank. The coolant flows from top to bottom through the fuel assemblies. Connected to the tank of the reactor, there is a 6 m deep rectangular auxiliary pool with water, used to store spent fuel. This pool is also used for operations that require a water shielding. Outside of the reactor core there are five beam tubes and a thermal column. One of the radial tubes is used for neutron radiography.

The current U3O8-Al core design has 24 Standard Fuel Assemblies (SFA) and 5 fork-type Control Fuel Assemblies (CFA), one in-core irradiation position and 8 ex-core irradiation positions.

One of the main objectives of the core improvements is to allow a more compact core to improve the irradiation fluxes, and to improve the operational cost reducing the number of FA consumed using a FA with higher uranium density and loading. The uranium consumption can also be improved trough a higher discharge burnup.

2. Fuel Assembly Design and Requirements

The design of the new FA is guided by several constrains from the current reactor design. Some of them are:

- Same core grid. It means the New U3Si2-Al FA has the same external dimensions as the Current U3O8-Al FA,
- No changes in the absorber area of the CFA
- Same Absorber Rods and its control and safety functions
- Minimize hydraulic perturbations in the core, it means similar coolant channels.

These design criteria will allow the usage of mixed core between the current core U3O8-Al and the new U2Si2-Al equilibrium core.

The main characteristics of the U3Si2-Al Fuel Assembly and its comparison with the current U3O8-Al FA can be seen in the Table 1.

Table 1: U3O8-Al and U3Si2-Al FA parameters

Parameter	**U3O8-Al**	**U3Si2-Al**
Meat Thickness.(cm)	0.1	0.074
Internal. Cladding. (cm)	0.038	0.037
External. Cladding (cm)	0.045	0.045
Internal. Channel. (cm)	0.33	0.33
External Channel. (cm)	0.165	0.148
SFA U Mass (grams)	1418	2330
SFA U_{235} Mass (grams)	280	460
Number of Fuel Plate per SFA	16	17
Number of Fuel Plate per CFA	12	13
Core Characteristics		
Number of SFA in the core	24	17
Number of CFA in the Core	5	5
Total number of Fuel Plate	444	388

3. Core Design and Requirements

The same thermal hydraulic design criteria will be applied.

- The minimum number of FA in the core is 21
- The maximum allowed heat flux is 102.3 Watt/cm^2

The same nuclear safety design criteria will be applied.

- The total control rod worth must be bigger than 150% the total excess of reactivity
- The worth of each control and safety rod must be in the range:
  780 pcm < CRWi < 6000 pcm.
- Shutdown margin must be greater than 3000 pcm
- Shutdown margin with single failure must be greater than 1000 pcm.
- The worth of the regulating rod must be lower than 780 pcm.
- The total reactivity worth of the experiments must be lower than 600 pcm.

The number and the requirements of the irradiation positions are summarized in the Table 2.

Table 2: Irradiation Position requirements

<table>
<tr><td>Type</td><td>Thermal Flux</td><td>Volume</td></tr>
<tr><td>In-Core (central)</td><td>> 2.0 E14</td><td>5 cm Diam. 24.6 cm height</td></tr>
<tr><td>In-Core (lateral)</td><td>> 1.5E14</td><td>2*1.4*1.4 cm2, 61.5 cm height</td></tr>
<tr><td>Ex-Core (peripheral)</td><td rowspan="3">Similar to current U3O8-Al core</td><td rowspan="3">7.7*8.1 cm2, 61.5 cm height</td></tr>
<tr><td>Ex-Core (reflector)</td></tr>
<tr><td>NAA</td></tr>
</table>

4. Design Tools

The Calculation tools used for the numerical analysis of the U3Si2-Al equilibrium core are the WIMS[2] and CITVAP[3] codes both available in the MTR_PC v3.0 system.[4]

WIMS code model uses the collision probabilities option in one dimensional geometry (slab) and it is used for cell calculation of all the core components (SFA, CFA, Be and Graphite, Control absorber, etc). The POS_WIMS [5] code were used to condense and homogenize the required cross section.

The HXS [6] utility is used to save the XS in a Macroscopic cross section Library, which can be very easily used in the CITVAP code.

The CITVAP reactor calculation code is a new version of the CITATION-II code[7], developed by INVAP's Nuclear Engineering Department. The code was developed to improve CITATION-II performance. The code solves 1, 2 or 3-dimensional multi-group diffusion equations in rectangular or cylindrical geometry. Spatial discretization can also be achieved with triangular or hexagonal meshes. Nuclear data can be provided as microscopic or macroscopic cross section libraries

The CITVAP model is a 3D XYZ model (as can be seen in Figure 1) in a 3 group's diffusion calculation. The upper energy limits of each group are: 10MeV, 0.821 MeV, and 0.625 eV.

5. U3Si2-Al Equilibrium Core Analysis.

The Figure 1 shows the core configuration, fulfilling the minimum number of FA and the in-core and ex-core irradiation positions.

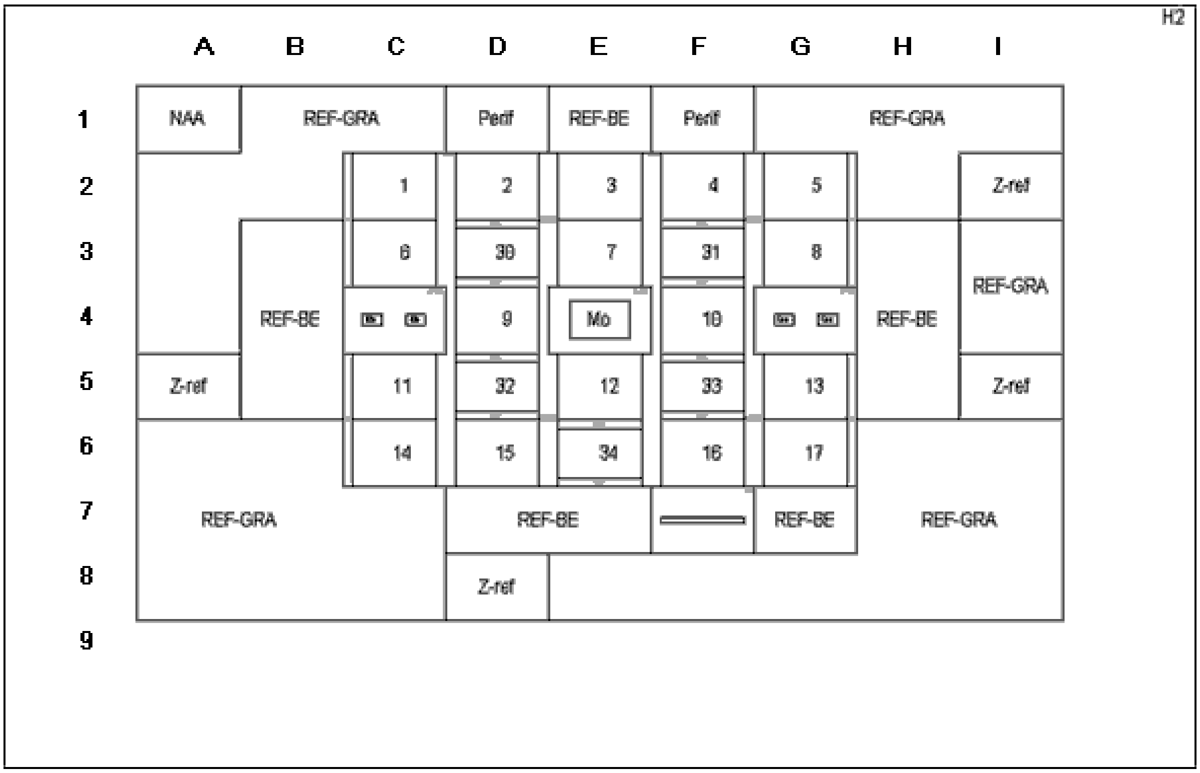

Figure 1: 24 FA Core configuration

The Table 3 shows the fuel management strategy used for the equilibrium core analysis; a minimum EOC reactivity of 1000 pcm is used and the cycle length needed to get this minimum reactivity is 20 days operating at 10MW.

Table 3: Refueling Strategy for 24 FA core

FM Chain	Sub-Cycle	Fuel Assembly movements
SFA Chain 1	1	Fresh SFA to position 14 to 2 to 6 to 9
SFA Chain 2	2	Fresh SFA to position 5 to 4 to 8 to 3
SFA Chain 3	3	Fresh SFA to position 17 to 15 to 16 to 13 to 7
SFA Chain 4	4	Fresh SFA to position 1 to 11 to 12 to 10
CFA Chain 1	5	Fresh CFA to position 34 to 31
SFA Chain 1	6	Fresh SFA to position 14 to 2 to 6 to 9
SFA Chain 2	7	Fresh SFA to position 5 to 4 to 8 to 3

SFA Chain 3	8	Fresh SFA to position 17 to 15 to 16 to 13 to 7
SFA Chain 4	9	Fresh SFA to position 1 to 11 to 12 to 10
CFA Chain 3	10	Fresh CFA to position 34 to 32
SFA Chain 1	11	Fresh SFA to position 14 to 2 to 6 to 9
SFA Chain 2	12	Fresh SFA to position 5 to 4 to 8 to 3
SFA Chain 3	13	Fresh SFA to position 17 to 15 to 16 to 13 to 7
SFA Chain 4	14	Fresh SFA to position 1 to 11 to 12 to 10
CFA Chain 3	15	Fresh CFA to position 34 to 33
SFA Chain 1	16	Fresh SFA to position 14 to 2 to 6 to 9
SFA Chain 2	17	Fresh SFA to position 5 to 4 to 8 to 3
SFA Chain 3	18	Fresh SFA to position 17 to 15 to 16 to 13 to 7
SFA Chain 4	19	Fresh SFA to position 1 to 11 to 12 to 10
CFA Chain 4	20	Fresh CFA to position 34 to 30

With this fuel management strategy the equilibrium cycle has 20 sub-cycles and the number of FA consumed for every 400 FPD is 16 SFA and 4 CFA. The Table 4 shows the main neutronic parameters of the Equilibrium core.

Table 4: Main Equilibrium Core Parameters

Parameter	Value	Comment
Cycle Length	20 Days	At 10 MW
Average SFA discharge Burnup	53.33%	
Average CFA discharge Burnup	67.45%	
Maximum SFA Discharge Burnup	62.34%	Sub-Cycle 8
Maximum CFA Discharge Burnup	70.47%	Sub-Cycle 10
Max. Hot Full Power Reactivity	3520 pcm	At BOC Sub-cycle 16
Min. Hot Full Power Reactivity	1559 pcm	At EOC Sub-cycle 8
Max. Hot Zero Power Reactivity	6737 pcm	Xe Worth 3217 pcm
Min. Hot Zero Power Reactivity	4832 pcm	Xe Worth 3273 pcm
Max. Cold Zero Power Reactivity	6889 pcm	Cold-Hot Reac. 153 pcm
Min. Cold Zero Power Reactivity	4987 pcm	Cold-Hot Reac..159 pcm
Max. Power Peaking Factor	2.57 (94 W/cm^2)	EOC Sub-Cycle 15
Maximum Thermal Flux E4	2.70E+14	EOC Sub-Cycle 7
Minimum Thermal Flux E4	2.64E+14	BOC Sub-Cycle 19
Maximum Thermal Flux C4	1.87E+14	EOC Sub-Cycle 12
Minimum Thermal Flux C4	1.72E+14	BOC Sub-Cycle 16
Maximum Thermal Flux G4	1.72E+14	EOC Sub-Cycle 10
Minimum Thermal Flux G4	1.58E+14	BOC Sub-Cycle 12
Average Thermal Flux D1	8.54E+13	
Average Thermal Flux F1	8.42E+13	
Average Thermal Flux I2	4.31E+13	
Average Thermal Flux A5	6.13E+13	
Average Thermal Flux I5	5.63E+13	
Average Thermal Flux D8	6.68E+13	
Average Thermal Flux A1	3.16E+13	NAA

The Table 5 shows the verification of the design criteria.

Table 5: Design Criteria Verification

Criteria	Limit	Current value
Number of FA	≥ 21	22
Maximum PPF	2.80 (102.3 W/cm^2)	2.57 (93.9 W/cm^2)
Minimum EOC reactivity	≥ 1000 pcm	1559 pcm (reserve for experiments)
CRW / Maximum Excess of reactivity	≥ 150%	294%
Minimum Control Rod Worth	≥ 780 pcm	2356 pcm
Maximum Control Rod Worth	≤ 6000 pcm	4074 pcm
Shut Down Margin	≥ 3000 pcm	14754 pcm
Shut Down Margin with Single failure	≥ 1000 pcm	5881 pcm
Regulating rod worth	≤ 780 pcm	713 pcm
Avg. In-Core Thermal Flux (E4)	≥ 2.0E+14	2.67E+14
Avg. In-Core. Thermal (C4,G4)	≥ 1.5E+14	1.72E+14
Ex-core Facilities (level 1)	~ 8.0E+13	8.48E+13
Ex-core Facilities (level 2)	~ 4.0E+13	5.69E+13
NAA	~ 2.0E+13	3.16E+13

4. Fuel Consumption

The number of FA consumed every 400 FPD is 16 SFA + 4 CFA.

To compare with the U3O8-Al FA an annual consumption will be calculated based in 300 FPD per year the information of the Fuel Management strategy for the U3O8-Al FA is extracted from reference [8].
The following table shows the number of SFA and CFA consumed per year and the Annual consumption of U235.

Table 6: Annual consumption (for 300 FPD)

Parameter	**U3O8-Al**	**U3Si2-Al**
Number of SFA	21.4	12
Number of CFA	5.4	3
Mass of U-235 (grams)	7127	6579

The improvement in the Uranium consumption is about 8% and the number of FA needed per year is almost half of the U3O8-Al case.

5. Conclusions

The proposed core fulfills all the design criteria.

The number of FA consumed per year is significantly reduced.

The proposed FA and core configuration improve the irradiation flux and volume in the in-core facilities.

- In the U3O8-Al core configuration there is only one in-core facility with a thermal flux of about 1.2E+14 n/cm^2/sec, and
- In the U3Si2-Al core there are 2 in-core irradiation facilities with a thermal flux bigger than 1.5E+14 n/cm^2/sec and one with flux bigger than 2.0E+14 n/cm^2/sec.

This preliminary analysis presented shows the potential improvements can be obtained with the change of the fuel type in the RP-10 core.

5. References

[1] IPEN- RP-10 home-page http://www.ipen.gob.pe/site/infraestructura/rp10_01.htm

[2] ASKEW, FAYERS AND KEMSHELL, **A general description of the lattice code WIMS,** UKAEA, 1967.

[3] EDUARDO VILLARINO, **CITVAP v3.2 Improved version of CITATION II**. MTR_PC v3.0 system: User manual. November 2001.

[4] EDUARDO VILLARINO, **MTR_PC v3.0 system**: User manual. November 2001.

[5] EDUARDO VILLARINO, **MTR_PC v3.0 User Manual: POS_WIMS ,** November 2001.

[6] EDUARDO VILLARINO, **MTR_PC v3.0 User Manual: HXS 4.1,** November 2001.

[7] FOWLER, T. B.; VONDI, **D. R., Nuclear Core Analysis Code: CITATION**, ORNL-TM-2496, July 1969.

[8] ESTUDIO DE LA GESTION DE COMBUSTIBLE DELREACTOR RP-10" Manahu Higa y Marcelo Madariaga, CNEA, 10 de Febrero del 1987.PE01 0699-0407-0001-JG-00