

**RERTR 2009 - 31st INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS**

November 1-5, 2009
Kempinski Hotel Beijing Lufthansa Center
Beijing, China

**RA-6 REACTOR CONVERSION AND NEUTRONIC TESTS OF THE
NEW SILICIDES FUEL CORE**

H. R. Blaumann, J. M. Longhino, F. Sánchez, E. Lopasso, F. Lezczycynski, D.
Ferraro, F. Brollo, C. Fernández
Department of Nuclear Engineering
Centro Atómico Bariloche, Comisión Nacional de Energía Atómica
Avda. Bustillo Km 9.5, 8400 S. C. de Bariloche, Río Negro, Argentina

and

A. Gómez, P. Bellino
Department of Reactors and Nuclear Power Plants
Centro Atómico Constituyentes, Comisión Nacional de Energía Atómica
Avda. Gral. Paz 1499, B1650KNA, San Martín, Buenos Aires, Argentina

ABSTRACT

The RA-6 reactor is located at Bariloche Atomic Centre and it is owned and operated by the Argentinean National Atomic Energy Commission (CNEA). It was commissioned in October 1982 and it has been operated at 500 kW with high enrichment fuel elements until June 2007.

A project focused on the core conversion and reactor power upgrade was initiated in April 2005 and completed in June 2009 with the support of the US Department of Energy (DOE).

Core design was based on low enriched (19.7%) uranium silicides, including burnable poisons. CNEA provided the new fuel elements. Significant modifications were performed in the reactor for the new operating conditions.

Results for the critical approach and the critical configurations implemented during the commissioning stage, together with excess reactivity measurement, the void and temperature reactivity coefficients measurements and the reduced prompt neutron lifetime measurement were evaluated and compared and with the design calculations.

1. Introduction

The RA-6 reactor is a MTR open pool type reactor, cooled and moderated by light water. It was designed and built entirely in Argentina and it was commissioned in October 1982. It was initially fueled with 90% enriched uranium aluminide, curved plates, fuel elements that had been previously used in the RA-3 reactor (being the uranium originally imported from the US). Graphite blocks were used as reflector and cadmium plates as control rods in a variable core configuration implemented in an 8x10 grid.

The RA-6 reactor was designed as a teaching and training reactor to support the Nuclear Engineering career at the Balseiro Institute and to be a nuclear experimental facility for the Nuclear Engineering Department. Foreseeing the development of several irradiation facilities, 5 radial beam tubes (2 of them crossing the reactor tank), and a thermal column (with an inner and outer block) were included in the reactor design. In-core irradiation positions were also available.

Nowadays an Activation Analysis Laboratory is linked to the reactor. Its main activities are related to geophysical and environmental applications. Also a Boron Neutron Capture Therapy facility has been developed. Its clinical beam has been used for the treatment of human skin melanomas, and small animals experiments focused on the study of new drugs performance and new tumors applications. Other facilities like Neutron Radiography and Prompt Gamma Neutron Activation Analysis have been configured and are being optimized for studying hydrogen contents and distribution in storing materials and devices.

2. The UBERA6 project

In the frame of the Global Threat Reduction Initiative a cooperation agreement was signed between CNEA and DOE for the conversion of the RA-6 reactor from high to low enrichment, including the repatriation to the US of the spent 90% enriched fuel elements. This initiative provided the opportunity for up rating the reactor power up to 3 MW in order to optimize its current applications and to supporting the RA-3 reactor in the provision of radioisotopes for Argentina. In order to achieve this objective a new core with LEU fuel elements was developed. The design of the new fuel elements was based on low enriched (19.7 %) uranium silicides, including burnable poisons, considering the Argentine previous experience in the qualification of a similar fuel element type, developed for the OPAL reactor (Australia).

Cadmium control plates were replaced by Ag-In-Cd ones.

Other main plant modifications involved the primary and secondary cooling systems, the instrumentation system, the protection system and the electric system.

2.1. Fuel elements and control rods

Table 1 shows the main characteristics of the new silicides fuel elements. Control fuel elements have only 14 internal plates in order to allow a water gap for the

insertion of 2 control plates. Cadmium control plates were replaced by 80%Ag-15%In-5%Cd, AISI 304L covered.

Table 1: Standard and control silicides fuel elements characteristics

FUEL ELEMENT	STANDARD	CONTROL
Total length [cm]	91.5	161.1
Fuel plates		
Quantity	17 internal plates	14 internal plates
	2 external plates	
Dimensions (HxWxT) [cm]	External plates: 73.5 x 7.05 x 0.15	
	Internal plates: 67.1 x 7.05 x 0.15	
Cladding material	Type 6061 aluminum	
Fuel meat		
Dimensions (HxWxT) [cm]	61.9 x 6 x 0.051	
Material	Al – U ₃ Si ₂	
Nominal densities [g/cm ³]	Al	1.364
	U ₃ Si ₂	5.179
	U	4.8
U enrichment	19.7 wt% of ²³⁵ U	
Burnable poisons		
Material and Geometry	Cadmium wires	
Quantity	20	16
Length [cm]	50 +/- 2	
Diameter [cm]	0.0500 +/- 0.0025	
Side walls		
Material	Type 6061 aluminum	
Dimensions (HxWxT) [cm]	78 x 8 x 0.5	147.6 x 8 x 0.5
Crossbar and Nozzle		
Material	Type 6061 aluminum	

2.2. Core configuration

Figure 1 (L) shows the planned new full operation core, defined in order to fulfill the regulatory requirements and to optimize the use of the lateral beam tubes and the BNCT facility.

2.3. Primary and secondary systems

The primary system flow rate was increased from 140 m³/h to 340 m³/h (limit value for assuring enough NPSH at the primary circuit pump entry) in order to dissipate the higher power. The secondary system flow rate was increased from 100 m³/h to 300 m³/h.

The following related modifications were performed (see Figure 1 (R)):

- primary and secondary pumps replacement
- heat exchanger replacement
- passive siphon break replacement by an active siphon break (primary system)
- single flap valve replacement by a double flap valve (primary system)
- primary and secondary orifice plates replacement
- cooling tower replacement (secondary system)
- piping replacement

2.4. Instrumentation system

The following modifications were performed:

- core pressure drop measurement system implementation
- power level reference by N^{16} activity measurement system implementation
- continuous gas effluent monitoring system implementation

2.5. Reactor protection system

The following modifications were performed:

- SCRAM for core pressure difference signal level and rate incorporation
- SCRAM for siphon break system failure incorporation

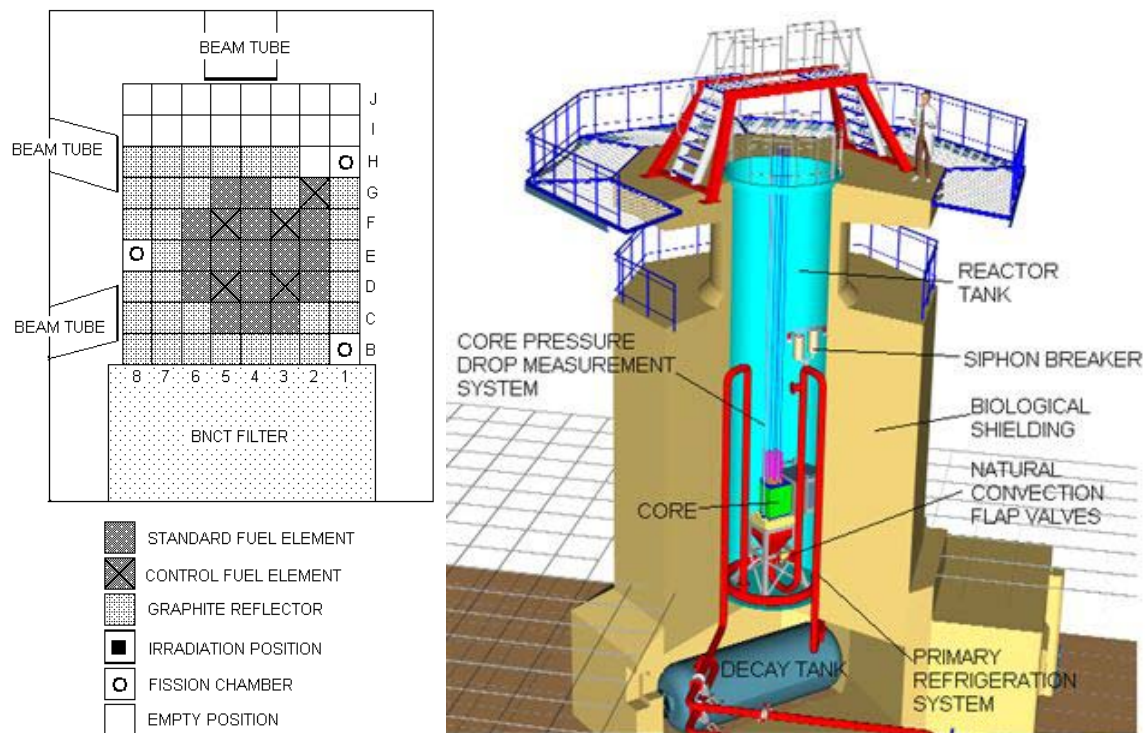


Figure 1: (L): Full operation core configuration. (R): Schematic view of the RA-6 reactor

2.6. Main project tasks packages

In order to perform these modifications, the following groups of tasks were developed:

Core engineering:

- fuel element definition; critical core, start up core, fresh and equilibrium full operation core configurations calculation; fuel assembly technical specifications formulation, peaking factor calculation; reactivity feedback coefficients and kinetics parameters evaluation
- maximum admissible flow rate in the primary circuit; flow rate determination in the different core channels (hydraulic experiment); convection coefficients determination (thermal experiment); hot channel characterization; heat exchanger,

pumps and cooling towers technical specification formulation

Thermal experiments were required for the assessment of the convection coefficients due to the “transition” flow rate regimen present in the reactor core.

Radiological safety analysis: shielding calculations, liquid waste and gaseous release evaluation for the new operative conditions; engineering and implementation of a continuous gaseous release monitoring system engineering and implementation, pneumatic irradiation facility modification; area monitors relocation.

Plant engineering: primary and secondary circuits lay out; siphon breaker design and implementation, the core pressure drop monitoring system design and implementation, the electrical system reviewing and fitting for the new operative condition and the instrumentation and control system reviewing and fitting to the new operative conditions.

Licensing: completion of new safety studies, not only due to the modifications but also to accomplish the new regulatory frame together with the renewing of the Safety Analysis Report and the relevant reactor documentation (Code of Practice, Operation Manual, Maintenance Manual, DIQ, etc)

Commissioning: planned and implemented according to [1], considering the Argentine regulatory requirements and developed in the following four steps:

B1: critical approach and critical configuration tests

B2: start up core configuration implementation and low power tests

C1: intermediate power tests

C2: full power tests

As the thermal experiment evaluation had not been completed when the commissioning stage begun, a conservative value of 1 MW for the maximum power was assumed.

3. Neutronic tests of the new silicide fuel core

3.1. Critical approach test

The initial silicides fuel elements core configuration contained 9 standard fuel elements and 4 control fuel elements as shown in Figure 2 (R).

Two standard fuel elements were loaded in the first step (C3 and C5) and then, one standard fuel element per step (D2, D6, F6, G5, F2), while measuring the fission chambers response and plotting the inverse multiplication against the number of fuel elements, shown in Figure 3 (R), until first criticality was achieved.

The minimum critical core contained 16 standard fuel elements and 4 control fuel elements as it is shown in Figure 2 (L). The minimum critical mass was determined to be 6433.75 g.

Criticality was achieved with control rods 1 to 3 (F3, D3, D5) fully withdrawn and control rod 4 (F5) withdrawn up to 59.5% of its length. MCNP calculations [2] resulted in a reactivity of -125 pcm for this configuration and control rod positions.

Excess reactivity for this configuration was measured through the calibration of the inserted length of control rod 4 by inverse kinetics [3], resulting in 720 pcm; while calculated value was 717 pcm [2].

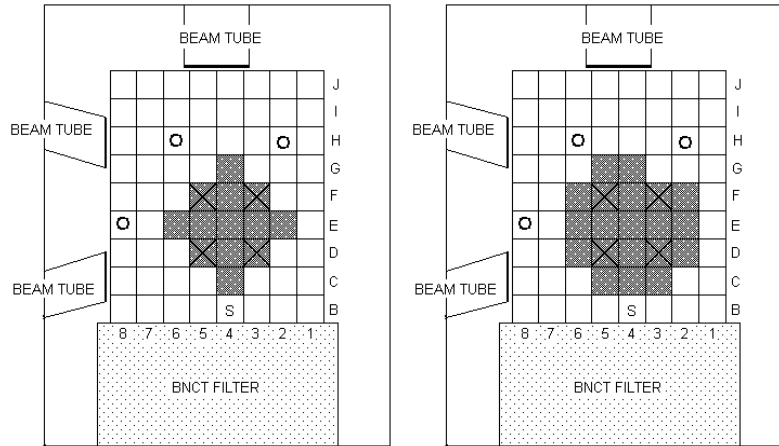


Figure 2: (L): The Initial core configuration. (R): The first critical core configuration

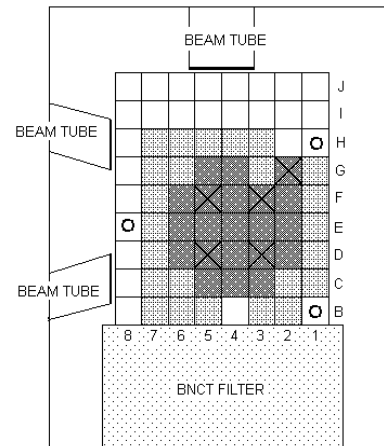
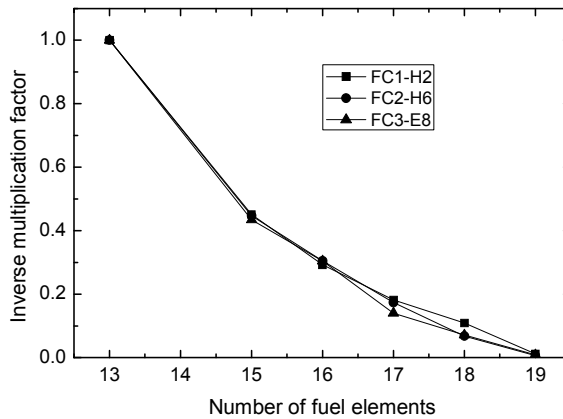


Figure 3: (L): The inverse multiplication factor curve. (R): Start up core configuration

3.2. The start up core configuration and neutronic tests

As due to regulatory requirements, the RA-6 reactor core must be subcritical with the 2 higher reactivity worth control rod fully withdrawn, a start up core (with lower excess reactivity than the operation one) was defined. It is shown in Figure 3 (R). It was implemented in 4 steps from the first criticality configuration by replacing one standard fuel element by a control element, as well as the regulating control rod, and gradually adding graphite reflectors. A control rod critical approach was performed for each intermediate configuration.

Once the start up core had been configured and the fission chambers as well as the ionization chambers relocated, stages B2, C1 and C2 were completed, including the following tests:

3.2.1. Excess reactivity measuring test

The excess reactivity was determined by calibrating the inserted length of the inserted control rods, using the inverse kinetics method. The measured value was

5346 pcm; while the calculated value by deterministic methods, using CONDOR [4] cell code and PUMA [5] diffusion code was 4379 pcm [6].

3.2.2. Control rod reactivity worth measuring test

Each control rod was calibrated by the compensation method, using inverse kinetics. Measured and calculated results are shown in Table 2. Calculated values [6] are in good agreement with measured ones (differences about 5%)

Table 2: Measured and calculated control rod reactivity worth

Control rod position	Measured reactivity worth [pcm]	Calculated Reactivity worth [pcm]
D3	3384	3246
D6	3958	3724
F6	4089	3856
F3	2618	2589
G2	982	987

3.2.3. Shutdown margin measurement test

The shutdown margin was measured by the integral rod drop method. The resulting value was 8961 pcm; while the calculated one [6] was 10380 pcm.

3.2.4. Thermal neutron flux distribution and peaking factor evaluation

The power peaking factor (PPF) was measured by correlating measurements with core calculations by Eq 1: the calculated PPF^C [6] is adjusted by a factor of calculated power densities, P_i^C , and measurements by copper activation rates, R_i^E , in some selected positions. The coefficients c_i are the ratios between calculated power density and calculated Cu reaction rates, and v_i are the volumes of calculation cells around each point i . The superscript m denotes the maximum of the measured set of points.

$$FPP^E = FPP^C \frac{\frac{c_m \cdot R_m^E}{\left(\sum_{i=1}^n c_i R_i^E v_i \right)}}{\frac{P_m^C}{\left(\sum_{i=1}^n P_i^C v_i \right)}} \quad (1)$$

This method allows the use some important information given by the calculations such as maximum power magnitude and position. A total of 249 points were monitored by irradiating copper-gold alloy (1.55 % Au) wires positioned on aluminum blades. Cu⁶⁴ and Au¹⁹⁸ activity was then measured for each sample in a 10% N-type HPGe. The resulting peaking factor was 2.48 ± 0.3 (1σ), 15% over the calculated value.

The position of the maximum calculated power density was coincident with the position of the maximum measured Cu⁶⁴ activity.

Once the calculated copper reaction rates were normalized with the mean value of the calculated to measured ratio, 80% of the calculated values lie within the 10% of the measured ones; and 97% of them lie within the 20%.

Figure 4 (L) shows a vertical profile for copper activation and copper to gold activation ratio measured in the central channel of the E4 position (Figure 5)

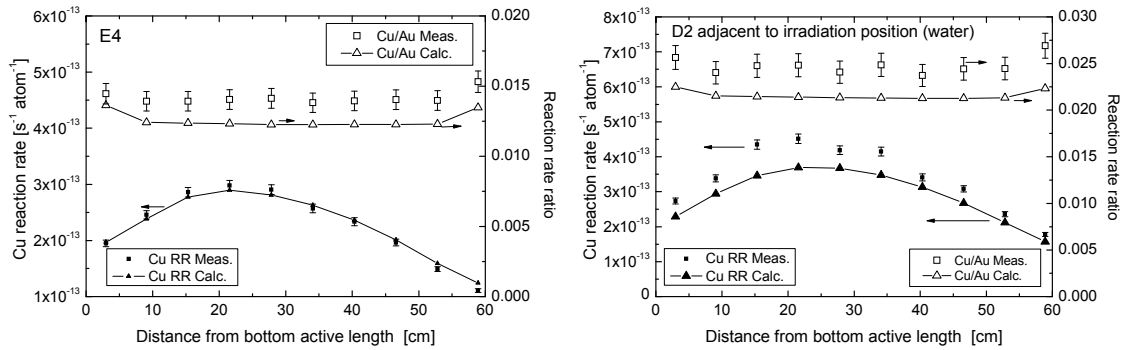


Figure 4: Vertical profile for copper activation and copper to gold activation ratio measured in the central channel of the E4 position (L), and in the D2 position in a channel adjacent to a water filled irradiation position (R).

Figure 4 (R) shows a vertical profile for copper activation and copper to gold activation ratio measured in the position D2 in a channel adjacent to a water filled irradiation position.

Differences in measured-calculated copper to gold activation ratio are about 10% in both cases; but differences in measured-calculated copper activation increase for the fuel element close to the irradiation position.

3.2.5. Void reactivity coefficient measurement test

Aluminium blades with 1 mm thickness were introduced in the central channel (thus removing moderator) of each standard fuel element for simulating void effect in the reactor core.

Criticality with and without the aluminium plates was achieved with the same positions for all control rods except for the regulating one, and the difference in its inserted fraction was then calibrated by the inverse kinetics method.

From MCNP calculations [7] an equivalent (that produces the measured reactivity) homogeneous moderator void fraction was determined (1.5%), being the void reactivity coefficient the ratio between the measured reactivity and the equivalent homogeneous void fraction.

The resulting value was -302 pcm/%; while the calculated value [6] was -302 pcm/%

3.2.6. Temperature reactivity coefficient measurement test

An isothermal temperature reactivity coefficient was measured by keeping the reactor critical at zero power, while increasing the core temperature. Core

temperature was increased by increasing the primary circuit temperature due to the power delivered by the main pump with the secondary system off.

Negative reactivity was continuously compensated by the regulating control rod, varying its length inserted fraction, which was then calibrated by the inverse kinetics method. The resulting measured value was $-14.2 \text{ pcm}/^\circ\text{C}$ while the calculated one was $-14.7 \text{ pcm}/^\circ\text{C}$ [6].

3.2.7. Power calibration

Power calibration was performed by means of the neutron noise technique [8, 9]. The test consisted in two stages: one at low power (1W - 10kW) in natural-convection regime, where the fission noise is preponderant and it is used for the power estimation; and the other stage at high power ($>10\text{kW}$) in forced-convection regime, where a gamma ionization chamber ($^{16}\text{N}-\gamma$) is used to measure the gamma emissions of the ^{16}N in the primary circuit, activated in its passage through the core of the reactor [10].

At the first stage, the noise measurements were done with two neutron ionization chambers (IC1 and IC2) placed in I4 and I6 (Figure 3 R). The Normalized Cross Power Spectral Density (NCPD) was measured and then fitted to obtain the power for each step. Measurements of currents $I_1(t)$ and $I_2(t)$ were performed and the calibration factors $f_1[\text{W}/\text{A}]$ and $f_2[\text{W}/\text{A}]$ were obtained by means of the linear correlation between I_1 , I_2 and the power.

At the second high power stage, the IC1 was moved to the J8 position of the grid and a new value for f_1 was obtained. Then, measurements of I_1 and $^{16}\text{N}-\gamma$ currents were performed and using the linear correlation (Figure 5 L) the calibration factor f_N was obtained. The resulting value was $f_N = (2.41 \pm 0.05) 10^{14} \text{ W}/\text{A}$, which was found to agree with the obtained by thermal balance.

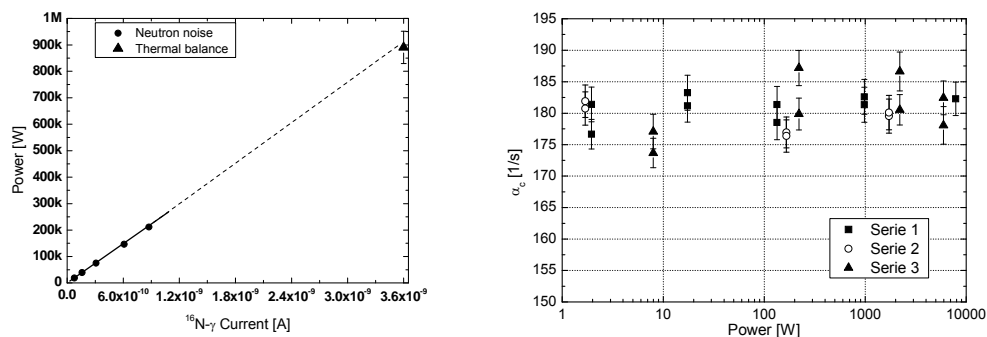


Figure 5: (L):Power vs $^{16}\text{N}-\gamma$ currents. (R): α_c measured values for the 3 series

3.2.8. Prompt neutron decay constant measurement test

Using the neutron noise technique, the prompt neutron decay constant was estimated. Simultaneously with the power calibration, the α_c (β/Λ) was estimated from the NCPD of two neutron ionization chambers placed at positions I4 and I6 (Figure 3 R). Three series of measurements were done during the first stage at low power (Figure 5 R). The resulting mean value was $\alpha_c = (180.2 \pm 0.6) 1/\text{s}$, whereas the calculated one was 185.1 s^{-1} [6].

4. Conclusion

RA-6 reactor conversion was completed and its power increased up to 1 MW. The commissioning tests results supplied the information for demonstrating that the start up core configuration fulfills the requirements of the regulatory body and provided a set of values for an adjustment of the calculational models in order to improve the design capabilities. A sensitivity analysis is being performed related to the calculated excess reactivity in order to evaluate its difference with the measured value.

Power increasing up to 3 MW will be completed by the end of next year.

5. Acknowledgments

UBERA6 project was completed with the financial support of the DOE and CNEA, and the technical support of the staff from several groups of CNEA who engaged with the conversion of the RA-6 reactor.

6. References

- [1] International Atomic Energy Agency; "Commissioning of Research Reactors". IAEA Safety Standards Series No NS-G-4.1. Safety Guide. IAEA, Vienna, 2006.
- [2] H. Blaumann, F. Sánchez. "Núcleos puesta en marcha", CNEA Technical Report ITA 06 NBX 707.
- [3] G. Robert Keepin, "Physics of nuclear kinetics". Addison-Wesley Publishing Company, Inc, 1965.
- [4] E. Villarino, "CONDOR v2.5 Neutron Calculation Code", Nuclear Engineering Division, INVAP.
- [5] C. Grant. "PUMA, sistema para la simulación del funcionamiento de reactores nucleares" CNEA, Technical Report CNEA-Re-163, Buenos Aires, 1980.
- [6] E. Lopasso. "Cálculo de parámetros del núcleo 11 para comparación con valores medidos", CNEA Technical Report ITA 06NBX 436
- [7] Weir A. "Cálculos de cambio de reactividad por fracción de vacío con el código MCNP5". CNEA Technical Report ITA-06NBX-412 Rev.1
- [8] Gomez A., Waldman R. and Laggiard E. Measurement of Power in Research Reactors Using the Neutron Noise Technique. Ann. Nucl. Energy, 1992. págs. 267-285, Vol. 19. No. 5
- [9] Gomez A. "Estimación del parámetro alfa y de la potencia en un reactor de investigación, mediante la técnica de ruido neutrónico", CNEA Technical Report ITE-06REC-215 (Rev 1).
- [10] F. Sánchez. "Diseño y descripción del sistema de medición de potencia por N16", Technical Report CNEA.ITA-06NBX-424.