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# PROGRAM FOR IN-PILE QUALIFICATION OF HIGH DENSITY SILICIDE DISPERSION FUEL AT IPEN/CNEN-SP

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## ABSTRACT

The development of high density nuclear fuel ($U_3Si_2$-Al) with 4,8 gU/cm$^3$ is on going at IPEN, at this time. This fuel has been considered to be utilized at the new Brazilian Multipurpose Reactor (RMB), planned to be constructed up to 2014. As Brazil doesn't have hot-cell facilities available for post-irradiation analysis, an alternative qualifying program for this fuel is proposed based on the same procedures used at IPEN since 1988 for qualifying its own $U_3O_8$-Al (1,9 and 2,3 gU/cm$^3$) and $U_3Si_2$-Al (3,0 gU/cm$^3$) dispersion fuels. The fuel miniplates and full-size fuel elements irradiations should be tested at IEA-R1 core. The fuel characterization along the irradiation time should be made by means of non-destructive methods, including periodical visual inspections with an underwater video camera system, sipping tests for fuel elements suspected of leakage, and underwater dimensional measurements for swelling evaluation, performed inside the reactor pool. This work presents the program description for the qualification of the high density nuclear fuel ($U_3Si_2$-Al) with 4,8 gU/cm$^3$, and describes the IPEN fuel fabrication infrastructure and some basic features of the available systems for non-destructive tests at IEA-R1 research reactor.

## 1. INTRODUCTION

Since 1988, IPEN has been producing and qualifying its own LEU (19.9% of $^{235}U$) MTR fuels for use in the IEA-R1 research reactor core. MTR fuel elements had been constructed with $U_3O_8$-Al dispersion fuel plates with densities of 1.9 (from 1988 to 1996) and 2.3 gU/cm$^3$ (from 1996 to 1999). Since September 1999, IPEN has been manufacturing $U_3Si_2$-Al dispersion fuel with uranium density of 3.0 gU/cm$^3$ [1].

In the last years, some high densities nuclear dispersion fuels ($U_3Si_2$-Al and U-Mo) are being studied at IPEN aiming future utilization in the IEA-R1 reactor core. Since the dispersion type fuel ($U_3Si_2$-Al, with the density of 4.8 gU/cm$^3$), that is already internationally qualified by the RERTR program and widely used since 1980's decade, it was defined to be used at the IEA-R1 core. Then, the development of high density nuclear dispersion fuel ($U_3Si_2$-Al) with 4.8 gU/cm$^3$ is on going at IPEN, at this time. In addition, this dispersion fuel ($U_3Si_2$-Al) has been considered to be used at the core of the new Brazilian Multipurpose Reactor (RMB), planned to be constructed up to 2014.

Fuel performance evaluation and nuclear fuel qualification require a post-irradiation analysis of this fuel. As IPEN have no hot cells to provide destructive analysis of the irradiated nuclear fuel, non-destructive methods have been utilized to evaluate irradiation performance of the fuel elements fabricated at IPEN/CNEN-SP.

## 2. QUALIFICATION PROGRAM OF THE HIGH DENSITY SILICIDE DISPERSION FUEL AT IPEN-CNEN/SP

The qualification program of the high density silicide dispersion fuel ($U_3Si_2$-Al, with 4.8 gU/cm$^3$) is based on the experience acquired at IPEN during the qualifications programs of the $U_3O_8$-Al (1.9 and 2.3 gU/cm$^3$) and $U_3Si_2$-Al (3.0 gU/cm$^3$) dispersion fuel. Two routes are foreseen to the qualification [2]. In the first one, fuel miniplates will be charged inside an irradiation device, designed and constructed at IPEN, and irradiated at IEA-R1 research reactor, up to reach 80% burnup (at. U-235). In the second route, a full size fuel assembly will be fabricated, containing two complete fuel plates ($U_3Si_2$-Al with density of 4.8 gU/cm$^3$) and sixteen dummy aluminum plates, that also will be irradiated in the IEA-R1 up to reach 50% burnup average (at. U-235). The density of 4.8 gU/cm$^3$ is the maximum qualified density in the world for this dispersion silicide nuclear fuel. The irradiation until the referred burnup will qualify the fuel assembly fabricated at IPEN. The utilization of the fuel in the maxima density already qualified will allow a better utilization of the fuel in the RMB, reduction in volume of the reactor core and the possibility of to increase the neutron fluxes and also the radioisotopes production for medical use in the country.

The proposed experimental program includes: (1) the manufacturing of fuel miniplates and irradiation at the IEA-R1 reactor core; (2) performing post-irradiation evaluations by means periodical tests and examinations based on non-destructive methods, during the irradiation time; (3) manufacturing of a full-size fuel assembly with two external fuel plates. To maintain the fuel element geometry and water cooling channels, the fuel assembly should be completed with sixteen “dummy” aluminum plates and, (4) manufacturing of an integral (standard) fuel element for irradiation at core reactor and evaluation of the fuel performance.

The complete fuel element evaluation consists of two items: (i) monitoring the fuel performance during the IEA-R1 operation, concerning the following parameters: reactor power, time of operation, neutron flux at the position of each fuel assembly, burnup, inlet and outlet water temperatures in core, water pH, water conductivity, chloride content in water, and radiochemistry analysis of reactor water; and (ii) periodic underwater visual inspection of the in-test fuel element and eventual sipping tests for fuel assembly suspect of leakage. Irradiated fuel assemblies have been visually inspected periodically by an underwater radiation-resistant camera inside the IEA-R1 reactor pool, to verify its integrity and its general plate surface conditions.

The qualification program includes the following steps:

### 2.1. Miniplate fabrication

Fabrication of fuel miniplates according the well established “picture-frame technique”. This technique has been used for years in commercial fabrication of aluminum-base dispersion fuel plates. The miniplates are produced by hot and cold rolling. Each miniplate consists of aluminum frame and cover plates. The frame contains a compact that is assembled in a cavity machined into the frame plate. These components are welded together by the roll-bonded cladding process. Figure 1 shows a schematic view of the basic miniplate assembling procedure. Figure 2 shows a schematic view of the picture-frame assembling after the rolling operation.


A B

**Figure 1 – Picture-Frame technique. A) Assembling B) After welding**

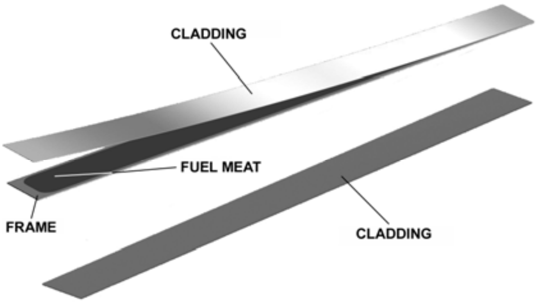


**Figure 2 – Fuel plate after the rolling operation.**

The fuel element fabricated at IPEN contains 18 fuel plates, each one 1.52 mm thick. Cladding and frame plates are made with the ASTM 6061 aluminum alloy. The fuel element results from mechanical assembling of 18 fuel plates and other structural components. Figure 3 shows the fuel element geometry.

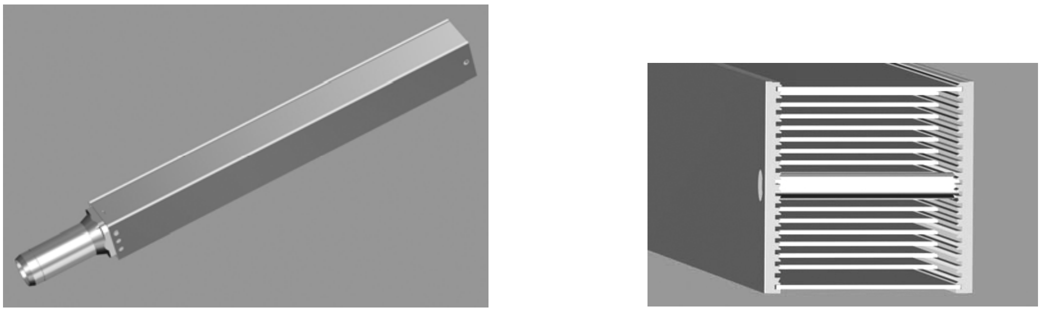


**Figure 3 – Fuel element fabricate at IPEN.**

Table 1 presents the main fuel meat characteristics of the fabricated miniplates. Figure 4 show a radiography taken from an $U_3Si_2$-Al miniplate. Figure 5 shows a radiography illustrating the final dimensions of the miniplate.

**Table 1. Characteristics of the fabricated miniplate fuel meats.**

| *Identification* | *Miniplate* **Thickness** | *Uranium Mass* | **Residual Porosity** | **Meat Dimensions** (mm) | | **Status** |
|---|---|---|---|---|---|---|
| | ***(mm)*** | ***(g)*** | ***(vol%)*** | *Length* | *Width* | |
| Si-E-01 | ***1.53*** | ***16.13*** | 10.44 | 114 | 42 | ***accepted*** |
| Si-E-02 | ***1.54*** | ***16.13*** | 12.06 | 117 | 42 | ***accepted*** |
| Si-E-03 | ***1.53*** | ***16.14*** | 12.03 | 115 | 42 | ***accepted*** |
| Si-E-04 | ***1.53*** | ***16.14*** | 12.36 | 115 | 42 | ***accepted*** |

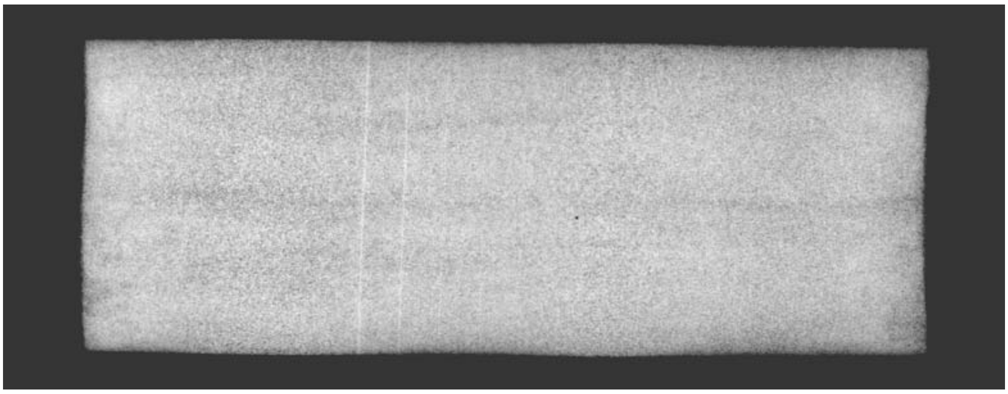


**Figure 4 – X-ray radiography taken from $U_3Si_2$-Al fuel meat (4.8 $gU/cm^3$)**

**Figure 5 – X-ray radiograph taken from a finished miniplate**

The cladding thickness in the finished miniplates was measured in seven regions of the fuel plate and was determined by means of metallography and image analysis. All the miniplates showed cladding thickness above the minimum specified. Figure 6 shows the microstructure of the meat of a miniplate, which is the typical appearance of the $U_3Si_2$-Al dispersion.

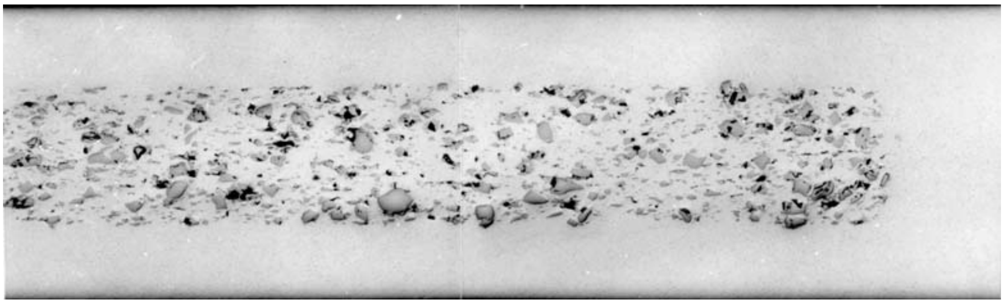


**Figure 6 – Typical microstructure of a non-irradiated $U_3Si_2$-Al miniplate.**

## 2.2. Miniplate irradiation

Miniplates with silicide $U_3Si_2$-Al with density of 4,8 gU/cm$^3$ was already fabricated. The irradiation device is already fabricated. The following steps are foreseen:

- Assess effect of to place in core the irradiation device with the fuel miniplates (neutronic, thermo hydraulics and security calculations).
- Comissioning of the irradiation device (for fuel miniplates) and the miniplate thickness measurement system designed and fabricated at IPEN.
- Fuel miniplates irradiation in the IEA-R1 research reactor up the maximum burnup for fuel qualification. Periodical evaluation of the fuel performance along the irradiation time, employing non-destructive analysis techniques.

## 2.3. Full-size partial fuel assembly

- Fabrication of a full size partial fuel assembly.
- Assess effect of to place in core the full size partial fuel assembly in IEA-R1.
- Fuel assembly irradiation at IEA-R1 up the maximum burnup for fuel qualification. Periodical evaluations by means the use of non-destructive analysis techniques.

## 2.4. Instrumented full-size fuel assembly

- Fabrication of an instrumented full size fuel assembly to obtaining thermo-hydraulics reactor core data.
- Operation of the IEA-R1 with the instrumented fuel assembly for data collection for evaluation of the thermo-hydraulics
- Assess effect of to place in core the full size partial fuel assembly in IEA-R1.

- Fuel assembly irradiation at IEA-R1 up the maximum burnup for fuel qualification. Periodical evaluations by means the use of non-destructive analysis techniques.

### 2.5. Modernization of the systems used for non-destructive techniques at IEA-R1

- Design and fabrication of an underwater pedestal for irradiated fuel assemblies visual inspection performing;
- Design and fabrication of an improved system for water samples collecting and sipping tubes holders. Sipping tests will be performed eventually in the fuel assembly and miniplates suspect of leaking of fission products in the reactor coolant.
- These devices should be used in the RMB posterior

## 3. QUALIFICATION EXPERIENCE

Since September 1997, the IEA-R1 research reactor employs only fuel elements manufactured at IPEN. The IEA-R1 fuel design follow rigorous technical specifications that were developed after a careful bibliography revision, comprising the world experience in the project, fabrication and fuel performance of dispersion fuels [3]. The qualification of these fuel elements was made in-use, which means that was based on their irradiation in the IEA-R1 research reactor followed by the use of non-destructive analysis techniques, mainly visual inspections performed regularly with a radiation-resistant underwater camera as well as sipping tests carried out eventually. Fuel performance evaluation can be summarized by the fuel assemblies average burnup achieved. Regarding the qualification of the MTR fuel elements manufactured at IPEN-CNEN/SP, by the end of January 2009, the highest average burnup achieved in the IEA-R1 research reactor for each type of LEU (19,9% enrichment) dispersion fuel already employed is presented in Table 2. The systems available at IEA-R1 are also described.

**Table 2. Highest average burnup achieved in the IEA-R1 research reactor by MTR fuel elements manufactured at IPEN-CNEN/SP (end of January 2009)**

| Dispersion fuel | Uranium density [gU/cm$^3$] | Fuel element | Status | Average burnup [%] at. $^{235}$U | |
|---|---|---|---|---|---|
| | | | | Calculated | Measured |
| $U_3O_8$-Al | 1,9 | IEA-130 | Spent | 36.10 [4] | (36.8 + 5.1) [5] |
| $U_3O_8$-Al | 2,3 | IEA-166 | Spent | 40.50 (*) | - |
| $U_3Si_2$-Al | 3,0 | IEA-169 | Spent | 43.50 (*) | - |

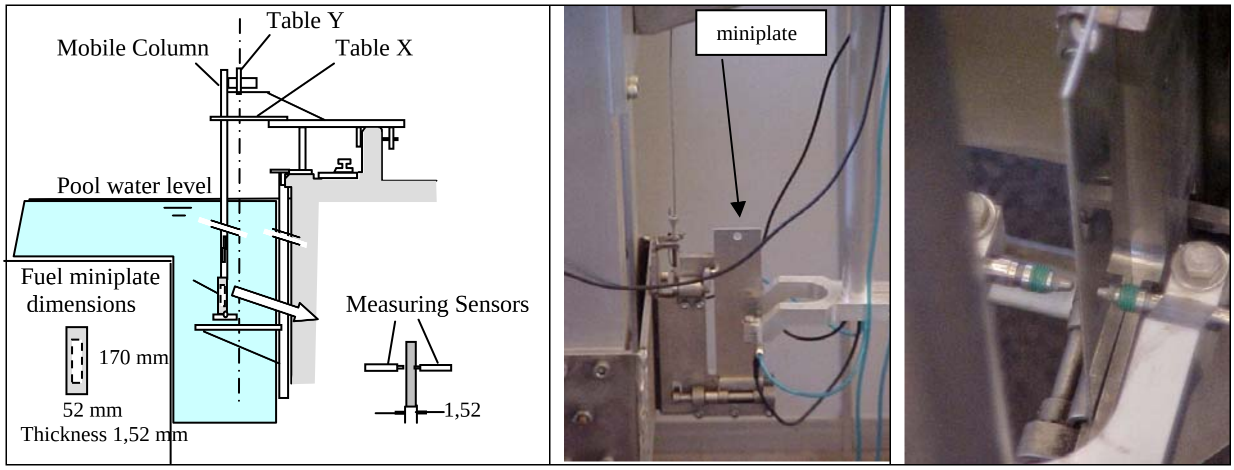
(*) According data supplied by the IEA-R1 reactor operator.

### 3.1. Visual inspection of irradiated fuel elements at IEA-R1

Irradiated fuel elements have been visually inspected by an underwater video camera system inside the IEA-R1 reactor pool, to verify its integrity and its general surfaces conditions. Basically, the available visual inspection system is composed by: (1) Underwater radiation resistant video camera (Black and White) equipped with zoom, auto-focus, iris, pan and tilt motion and, light intensity remotely controlled. (2) Non-radiation resistant color video camera system (IST Color Underwater Outstation – model R982) equipped with zoom and auto-focus system. (3) Endoscopy (optical fiber probe type) coupled with a small color camera system, which allows the visualization and obtaining images from internal fuel plate’s surfaces, along the fuel plate’s length. It is planned to use this equipment for visualization (in order to identify) the nature of the defect in the fuel element IEA-175, discharged from the IEA-R1 core, with a very low burnup. The video images obtained from the camera systems can be recorded by a videocassette recorder or a DVD recorder.

### 3.2. System for fuel miniplate thickness measurement

A system for fuel swelling evaluation, by means of the fuel miniplate thickness measurement during the irradiation time, was designed and constructed within the framework of IAEA Project BRA/4/047 and is available at IPEN/CENC. This device, showed at Fig. 7, shall be used inside the reactor pool, at the fuel storage area. It should be operated from the reactor pool border, and allows the measurement of the fuel miniplate thickness along its surface.



(A) (B) (C)

Fig 7. Fuel miniplate thickness measurement apparatus at IEA-R1: (A) schematic view at the reactor pool border; (B) lateral view; C) profile view (thickness).

The thickness measurement is performed by electronic probes (LVTD). The results are obtained by measurement instrumentation connected to the probes. Another work about this miniplate thickness measurement system is presented in this INAC 2009.

### 3.3. Sipping tests of irradiated fuel assemblies

Sipping test is a non-destructive technique employed to evaluate the structural integrity of the cladding of irradiated nuclear fuels, which is based on the detection of radioactive fission products leakage to the reactor coolant, usually by means of gamma-ray spectroscopy. Basically, the test consists in the storage of the fuel element suspect of leakage inside a recipient, called here as sipping tube, which contains water demineralised. After an initial homogenization it is collected the first water sample, characterized as background (BG) sample. After a given time in rest (four hours), compressed air is injected to promote a better water homogenization. The second water sample is collected from the sipping tube and characterized as the “sipping sample for that in test FE”. Additional data collection are: water temperature from inside the sipping tube, the sample collection time and the reactor power during the sipping test; as well the demineralised water characteristics used in the washing (pH, conductivity, chlorides). Radiochemistry analyses are made on the collected samples. The presence of chemistry elements fission products at the samples indicates the existence of some defective part in the fuel element cladding. A detailed description of the sipping tests performed at IPEN is presented at reference [6].

## 4. CONCLUSIONS

All the presented non-destructive methods and tests, with emphasis to the visual inspections and sipping tests, have been important tools to the characterization and verification of the general conditions and behavior, as well the integrity of the cladding of irradiated fuel element assemblies at the IEA-R1 reactor. These systems can be used during the fuel qualification of the $U_3Si_2$-Al (4,8 gU/cm$^3$) dispersion fuel.

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