# INSPECTION EXPERIENCE WITH IEA-R1 SPENT FUEL AND NON-DESTRUCTIVE METHODS FOR QUALIFICATION OF HIGH DENSITY LEU FUEL ($U_3Si_2$-Al) AT IPEN/CNEN-SP

J.E.R. SILVA, A.T. SILVA, L.A.A. TERREMOTO
*Fuel Engineering Group, Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN-SP)*
*Av. Professor Lineu Prestes, 2242, 05508-000 São Paulo, SP - Brazil*

## 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. As Brazil doesn't have hot-cell facilities yet 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 (2,3 and 3,0 gU/cm$^3$) dispersion fuels. Fuel miniplates, partials and integral fuel assemblies' irradiation should be performed at IEA-R1 core. The fuel characterization during the irradiation time should be made by means non-destructive methods including periodical visual inspections with 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 some basic features of the available systems for non-destructive tests at IPEN as well the inspection experience with IEA-R1 spent fuel assemblies.

## 1. Introduction

The IEA-R1 research reactor at IPEN/CNEN-SP in Brazil is a pool type research reactor of B&W design, cooled and moderated by demineralised water and having beryllium and graphite as reflectors. In 1997, the reactor received the operating licensing for 5 MW. 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].

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. The non-destructive analysis techniques have been an important part of the qualification program of the fuels manufactured at IPEN. Today, for utilization in the IEA-R1 reactor core, the $U_3O_8$-Al fuel is qualified up to a uranium density of 2,3 gU/cm$^3$ and the $U_3Si_2$-Al fuel up to a uranium density of 3,0 gU/cm$^3$. 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. Although, 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 1984 [2, 3] 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. For this fuel, it is proposed an experimental program 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. 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 partials fuel elements with (i) two external fuel plates and, (ii) ten fuel plates, both cases completed with “dummy” aluminium 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 fuel elements and eventual sipping tests for fuel element suspect of leakage. Irradiated fuel elements 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 [4]. The IEA-R1 fuels 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 [5].

## 2. Qualification of the MTR fuel elements manufactured at IPEN-CNEN/SP

In 1988, MTR fuel elements begun to be produced in IPEN-CNEN/SP and since September 1997, the IEA-R1 research reactor employs only fuel elements manufactured at IPEN. The qualification of these fuel elements is made in-use, which means that is 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 element average burnup at the end of its whole irradiation period in the reactor core. Regarding the qualification in-use 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 1.

| **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 [6] | (36.8 + 5.1) [7] |
| $U_3O_8$-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.

Tab 1: Highest average burnup achieved in the IEA-R1 research reactor by MTR fuel elements manufactured at IPEN-CNEN/SP (end of January 2009)

## 3. Systems Description

### 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 colour video camera system (IST Colour Underwater Outstation – model R982) equipped with zoom and auto-focus system. (3) Endoscopy (optical fibre probe type) coupled with a small colour camera system, received from IAEA in August 2007, which allows the visualization and obtaining images from internal fuel plates 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 recently 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. Sipping tests of irradiated fuel assemblies

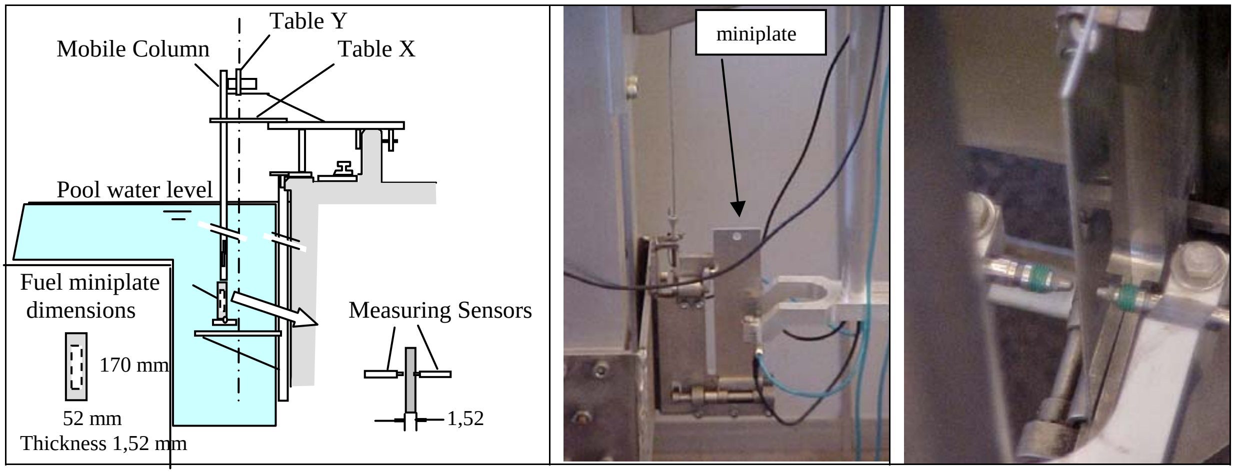
Sipping test is a non-destructive technique employed to evaluate the structural integrity of the cladding of irradiated nuclear fuels, which is based on the detection of radioactive fission products leakage to the reactor coolant, usually by means of gamma-ray spectroscopy. Basically, the test consists 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 [8].

### 3.2.1. Choice of failure monitor

For sipping tests on irradiated fuel elements stored for many years inside spent fuel pools, the most suitable fission product for use as a failure monitor is $^{137}Cs$, due to its long half-life (30,14 years), great fission yields and high solubility in water [9]. However, for sipping tests on newly irradiated fuel elements (or fuel miniplates), the choice of a failure monitor is not so obvious. Of course, great fission yields and high solubility in water remain indispensable characteristics of the radionuclide to be used. Nevertheless, in this case the radionuclide half-life must be much shorter, typically about some days, to provide a high specific activity in the sample and an easy identification in the gamma-ray spectrum. The gamma-ray spectra obtained from measurements on samples corresponding to the failed fuel element (IEA-156) show clearly that $^{131}I$ and $^{133}I$, radioactive isotopes of iodine with half-lives respectively equal to 8.02 days and 20.8 hours [10], are the suitable failure monitors in these conditions. An additional evidence for the choice of $^{131}I$ and $^{133}I$ as failure monitors regarding sipping tests on newly irradiated fuel elements is that, shortly after unwanted releases of fission products, these two radioiodine isotopes are the most easily detectable radionuclides by means of gamma-ray spectroscopy [11]. On the other hand, precise values for specific activity and average leaking rate of $^{131}I$ and $^{133}I$ are difficult to obtain, because their most prominent full-energy peaks, corresponding to gamma-rays with energies of 364.5 keV for $^{131}I$ and 529.9 keV for $^{133}I$, are partially overshadowed by Compton continua from many other gamma-rays with higher energy. Under these circumstances, for the case of the fuel element IEA-156, it was decided to wait 6 months to enable the decay of short-lived fission products and activation products in the samples, in order to measure the average leaking rate of $^{137}Cs$ from the failed fuel element to water.

## 3.3. 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. 3, 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 3. 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. For the miniplate thickness measurement, a mobile metallic column, held by a X-Y coordinate table system, is used. This table is supported by another metallic structure fixed at the border of the reactor pool.

## 4. Works and experience obtained

Several works related with the utilization of the mentioned NDT techniques on characterization of irradiated fuel elements were performed at IEA-R1. Some works are mentioned in following:

**Sipping tests at the spent fuel elements stored at IEA-R1:** In 1996, during the programmed activities to send back the 127 spent fuel elements stored in the IEA-R1 to USA (US-DOE American fuel take back program), sipping tests on 62 stored spent fuel elements were performed. At the conclusion of the tests were determinate which fuel element presented $^{137}$Ce escape to the water and also which was the liberation rate. It was done a correlation with the visible characteristic presented (corrosion pits on the external fuel plates).The Savannah River Side (SRS-DOE) team adopted this IPEN technique as a comparative basis for the MTR fuel transportation criteria in shielded casks and as a basis for future analysis at others MTR storage facilities, at the US-DOE program.

**Sipping tests for determination of the failed fuel element at IEA-R1**: In 2001, sipping tests besides visual inspection showed a defective fuel element (IEA-156). This FE was maintained stored in wet-storage conditions at IEA-R1 pool, inside an aluminium tube until November 2007, when it, together another 32 (total 33 fuel assemblies) were sent back to USA, by also the US-DOE American fuel take back program.

**Ordinary visual inspection of the fuel elements at IEA-R1:** Programmed visual inspections have been performed on the in-use fuel elements during the fuel element qualification time ($U_3O_8$-Al and $U_3Si_2$-Al), once in every three months from 1997 to 2001 and once in every six months from 2002 to nowadays.

**Sipping tests for determination of the failed fuel element at IEA-R1:** During March to July-2007, a campaign of sipping tests showed two defective U3Si2-Al that were loaded in core in the beginning 2007 (IEA-174 and IEA-175). Both fuel assemblies present very low burnup and were discharged of the core reactor and were stored at pool reactor racks.

## 5. 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.

## 6. References

[1] J.A. Perrotta; J.E.R. Silva, Estratégia de utilização de combustíveis MTR de alto teor de urânio para operação do reator IEA-R1 a 5 MW, 1996. VI Congresso Geral de Energia Nuclear, Rio de Janeiro, Brazil, Oct 27 to Nov 01, 1996, Proceedings of..., Vol. 1.

[2] M.B. Davis, 2008. La France nucleaire / Nuclear France: materials and sites. Uranium-aluminum and silicide fuel. Available at: http://www.francenuc.org/en_chn/reactors_e.htm.

[3] J.M. Park; H.J. Ryu; Y.S. Lee; H.T. Chae; C.K. Kim, 2008. Development of U-Mo Research Reactor Fuel in KAERI. In: 2008 International Symposium on Material Testing Reactors, July 16th - 17th, 2008 Available at: http://new-jmtr.jaea.go.jp/contenpage/symp/materials/B-3.pdf.

[4] A.T. Silva; L.A.A. Terremoto; J.E.R. Silva; C.T. Almeida; M.A. Damy; P.E. Umbehaun, M. Yamaguchi, 2008. Qualification program of research reactor fuels manufactured at IPEN-CNEN/SP. Elsevier. Progress in Nuclear Energy 50 (2008) 795-799,

[5] A.V. Simões, 1993. Desempenho sob irradiação de combustíveis a dispersão de MTR. Dissertação (Master of Science), Instituto de Pesquisas Energéticas e Nucleares, University of São Paulo, São Paulo (in Portuguese).

[6] M. Yamaguchi, 1997. Validação da Metodologia de Cálculo Neutrônico do Reator IEA-R1. Technical Report IPEN-CNEN/SP (in Portuguese).

[7] L.A.A. Terremoto; C.A. Zeituni; J.A. Perrotta; J.E.R. Silva, 2000. Gamma-ray spectroscopy on irradiated MTR fuel elements. Nuclear Instruments and Methods in Physiscs Research A 450, 495-514.

[8] C.A. Zeituni; L.A.A. Terremoto; J.E.R. Silva, 2004. Sipping tests on a failed irradiated MTR fuel element. PHYSOR 2004- The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments. Chigago, Illinois, April 25-29, 2004, on CD-ROM, Americam Nuclear Society, Lagrange Park, IL.

[9] J.A. Perrotta; L.A.A. Terremoto; C.A. Zeituni, 1998. Experience on wet storage spent fuel sipping at IEA-R1 Brazilian research reactor. Ann. Nucl. Energy 25 (4-5), 237-258.

[10] U. Reus; W. Westmeier, 1983. Catalog of gamma rays from radioactive decay – Part II. At. Data and Nucl. Data Tables 29, 193-406.

[11] R.K. Gopalakrishnan; P.M. Ravi; S.K. Prasad; M.R. Iyer, 1995. Failed fuel detection in-reactor coolant using radioiodine measurement. Nucl. Technol. 111 (1), 105-108.