2005 International Nuclear Atlantic Conference - INAC 2005
Santos, SP, Brazil, August 28 to September 2, 2005
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: 85-99141-01-5

DESIGN AND CONSTRUCTION OF AN IRRADIATION APPARATUS WITH CONTROLLED ATMOSPHERE AND TEMPERATURE FOR RADIATION DAMAGE EVALUATION OF NUCLEAR MATERIALS IN THE IEA-R1 RESEARCH REACTOR

Georgi Lucki, José Eduardo Rosa da Silva, Myrthes Castanheira, Luís Antonio Albiac Terremoto, Celso Antonio Teodoro, Antonio Teixeira e Silva, Margaret de Almeida Damy

Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
glucki@ipen.br

ABSTRACT

A material irradiation apparatus CIMAT (Cápsula de Irradiação de Materiais) with controlled temperature and atmosphere is described. The device was specifically designed to perform experiments inside the core of the IEA-R1 swimming pool reactor and allows fast neutron (E=1 Mev) irradiations of multiple miniature metallic samples at temperature between 100 °C and 500 °C, in Argon or Helium atmosphere to inhibit corrosion. The aim of CIMAT is to make a comparative assessment of Radiation Embrittlement (RE) on the AS 508 cl.3 steel, of different origins (ELETROMETAL-Brazil and VITCOVICE-Chekia) used in Pressure Vessels (PV) of PWR, for fluence of 10exp19 nvt at 300 C, by means of mechanical post irradiation evaluation. Previous characterization of non-irradiated samples of these materials is presented. In situ electrical and magnetic measurements, at high temperatures, are foreseen to be made with this apparatus. Extensive temperature stability and leak-tightness tests performed in the reactor swimming pool have proven the CIMAT to be intrinsically safe and operational

1. INTRODUCTION

CIMAT (Cápsula de Irradiação de Materiais) is a multipurpose irradiation device with controlled atmosphere and temperature. It represents an evolution of the irradiation capsules used at Melousine (Grenoble-France) and IEA-R1m (São Paulo-Brazil) materials testing reactors. It consists of:

a) irradiation tube
b) temperature regulator
c) capacity for electrical (resistivity) and magnetic (hysteresis and magnetic after-effect) measurements.

The specific features of the CIMAT allow in situ experiments (physical measurements during irradiation) and annealings from 100 °C to 500 °C by means of a low power (115 W) furnace, occupying a volume of a fuel element, nearby the reactor core.

2. IRRADIATION DEVICE

2.1. Working Principle

Complementing the Gamma Heating (GH), (see Table 1) an electrical furnace of cylindrical shape is used to heat the samples to the chosen experimental temperature. The irradiation tube is filled with Helium or Argon gas at a pressure of 1.2 bar with the purpose of improving the internal heat exchange, to inhibit the sample corrosion and provide intrinsic protection for the reactor in case a leakage occurs.

2.1.1. CIMAT capsule description

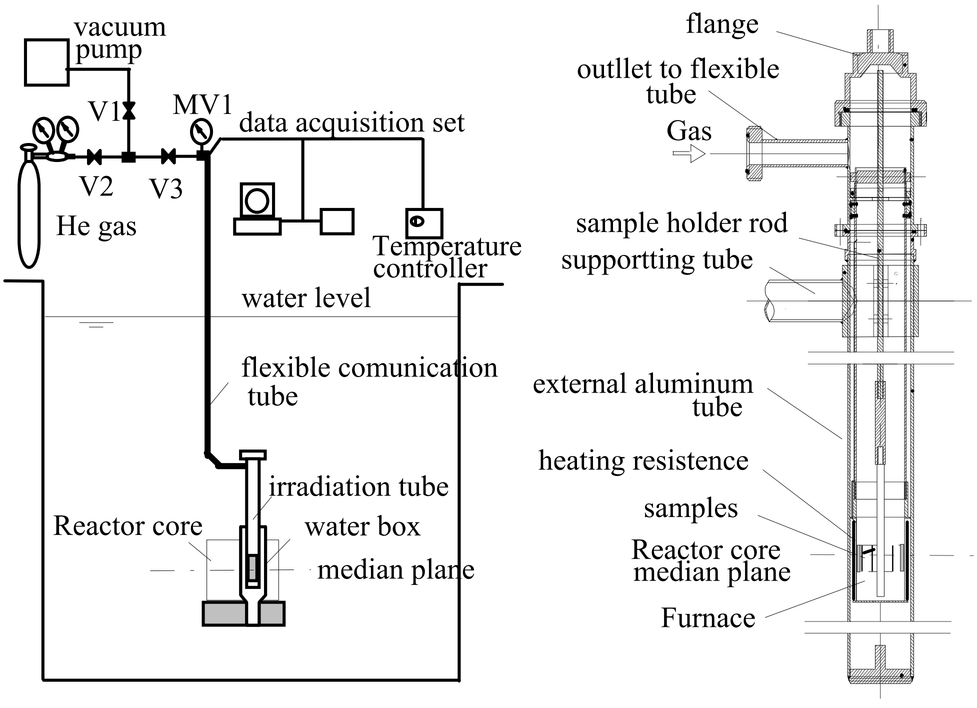

Figure 1. (a) Position of CIMAT in the reactor core
(b) and Irradiation tube schematics

The irradiation device is a leak-proof set comprising:

- irradiation tube made of aluminum (Al 6063 T5), 2,500 mm long, with internal and external diameters of 60 mm and 66 mm, respectively. This tube contains the furnace attached to an internal supporting tube made of same aluminum. The internal tube holds the median plane of the furnace at a position coincident with the median plane of the reactor; it also allows the removal of a defective furnace.
- a threaded flange, on the top of the irradiation tube permits the insertion and removal of the samples.
- an outlet flange, located above the water level, with electrical connections.
- an aluminum tube supporting the entire device.

- the electrical furnace is a cylinder made of 316 stainless steel, 102 mm long with internal diameter of 48 mm, 0,25 mm thick wall, inside which a sample holder is introduced, for high temperature irradiation. A “Thermocoax” (diameter=1 mm) heating element is wound on the furnace and temperature is controlled by a type K thermocouple (thc), fastened directly on the heating element, to assure a quick response to temperature fluctuations. A second thc, attached to the sample, monitors the sample temperature.

2.1.2. Sample insertion and removal

The sample insertion and removal are performed through a flange on the top of the irradiation tube by means of an extraction rod attached to the sample holder. The position of the flange was designed to simplify the removal of irradiated samples, as well as, of a defective furnace.

3. TEMPERATURE CONTROL

To simulate the working condition of a PWR, the nuclear materials – specifically the PV steel AS 508 cl.3 – are irradiated in reactor core at a pre-established temperature controlled by a temperature regulator. Since the furnace has small thermal inertia, the regulator must quickly compensate for the temperature fluctuation arriving from several sources, including the Gamma Heating (GH).

3.1. The Working Principle

To maintain the samples at a temperature T_s it is advisable to maintain the difference $T-T_s$, where T is the measured temperature, as small as possible. A thc attached to the sample holder shows the temperature variation of the sample. Another thc, in direct thermal contact with the resistive wiring of the furnace, promptly controls the electric current by means of a PID electronic temperature regulator (EVERY CONTROL MOD. EC-3-173).

4. THERMAL CALCULATION FOR CIMAT

4.1 Main Characteristics and Parameters

- maximum temperature of the furnace: 500 ^oC
- temperature of the irradiation tube: 35 ^oC (temperature of the swimming pool water)
- static Helium or Argon atmosphere (convection not considered)
- total length of CIMAT: 9,720 mm
- the sample temperature is due to: GH (Gamma Heating)+ EH (Electrical Heating)
- irradiation tube has internal and external diameters of 60 mm and 66 mm, respectively, and the Figure 1 shows the longitudinal section of the furnace at the level (median plane) of the sample positioning.
- gas gap = 4.75 mm; the sample holder is made of aluminum

4.2 Evaluation of the Gamma Heating GH

The following assumptions were made:
- the temperature gradient of the furnace is negligible, which is acceptable due to the fact that all experiments are to be performed in a region±5 mm, centered on the median plane of the furnace and the reactor core
- the GH is expressed in W/cm
- the thermal resistance of the gas gap, is defined as R = $(1/2\pi\lambda) \ln r_e/r_i$ = $(1/6.2832\ \lambda) \ln 3/2.525$ = $0{,}1724/6.2832\ \lambda$ = 27,4382 exp-3/λ, r_e and r_i are the external and internal radii of the gas gap, and λ is the thermal conductivity of the gas.
- establishing the gamma heating of the sample holder as GH_s; for the furnace as GH_f and the electric heating as EH, then the total temperature gradient ΔT is the sum of ΔT_s (sample holder) and ΔT_f (furnace); $\Delta T = \Delta T_s + \Delta T_f$ = R [GH_s] + R [GH_s+GH_f+EH]. Since only GH is presently of interest, EH=0, we may write, ΔT = R [2 GH_s + GH_f].

4.2.1. Gamma heating of IEA-R1

Table 1. Gamma heating of IEA-R1 critical at 2 MW, 3.5 MW and 5.0 MW

Reactor Power (MW)				2,0	3,5	5,0
Specific Gamma Heating (W/g)				0,25	0,44	0,62
	Irradiated Volume (cm^3)	Density (g/cm^3)	Mass (g)	Gamma Heating (W/cm)	Gamma Heating (W/cm)	Gamma Heating (W/cm)
Sample Holder (Al)	0.424	2.7	1.14	GH_s=0.29	GH_s=0.50	GH_s=0.71
Furnace 316 SS	0.379	7.9	2.99	GH_f=0.75	GH_f=1.32	GH_f=1.85

4.2.2. Evaluation of the sample temperature T_s due to Gamma Heating

a)-Helium atmosphere - 2 MW reactor power: - the thermal conductivity λ is a function of gas temperature, which in turn, is a function the sample temperature T_s. The average gas temperature is $\overline{T} = (T_s + 35)/2$ (°C) [35 °C is the water temperature]; the numerical values of λ=f ($\overline{T}$) were taken from [4]. For T_s =300 °C, we have $\overline{T}$ = 167,5 °C = 440,5 K; λ = 1.885 exp (-3) (W/cm °C) and R = 14.55 (cm °C/W). Replacing these data, we obtain ΔT = 19.35 °C. Physically ΔT represents the temperature difference between T_s and the water temperature, so that, T_s = ΔT + 35 = 54.4 °C. To reach the experimental temperature of 300 °C, the energy will be supplied by EH. In a similar procedure ΔT and T_s values are obtained for 3.5 MW and 5.0 MW (Table 2).

b)-Argon atmosphere – 2, 3,5 and 5 MW reactor power: λ = (0.2389 exp (-3) (W/cm °C) R = 114,852 (cm °C/W). ΔT and T_s, are stated in Table 2.

Table 2. Temperature gradient and sample temperature for helium and argon gases

Reactor Power (MW)		2.0	3.5	5.0
Specific Gamma Heating (W/g)		0.25	0.44	0.62
Heat Exchange Gas	ΔT Helium (^{o}C)	19.4	33.8	47.6
	T_s (^{o}C)	54.4	68.8	82.6
	ΔT Argon (^{o}C)	152.8	266.5	375.6
	T_s (^{o}C)	187.8	301.5	410.6

4.2.3. Electrical Heating (EH)

CIMAT has a 115.2 W electric furnace with the purpose of supplying the EH (complementary to the GH) necessary to maintain a determined experimental temperature. The temperature increase delivered by EH is: $\Delta T \propto R \times EH$, where: R= 140 Ω; (heating resistance); L=7cm (length); V=127 V (maximum voltage), then the maximum EH=16,46 W/cm. Experiments to test the temperature stability, with EH (CIMAT immersed in the swimming pool) were performed at 100, 150 and 200 ^{o}C showing temperature oscillations of ±1^{o}C. The temperature stability is attributed to the low thermal conductivity of the furnace made of SS 316, Argon gas, the rapid response of the electronic temperature regulator and good thermal contact of the thc with the furnace.

5. TENSILE TESTING RESULTS

The tensile experiments were performed on a universal testing machine to characterize the mechanical properties of AS 508 cl.3 steel used in PV of PWR. The non irradiated samples were tested as supplied [2] by ELETROMETAL (Brazil – E samples) and VITCOVICE (Chekia – V samples) aiming at mechanical characterization of the material at room temperature. The miniature samples are described in [2] and were tested accordingly the experience acquired at IPEN [3] [5] and follow the guide-lines of the ASTM [6], [7].

Table 3. Tensile test results of AS 508 cl.3 steel

Sample	Maximum Load (N)	Yield Stress (MPa)	Elongation (%)	Elasticity Modulus (MPa)
E	147 ± 5	583 ± 19	16 ± 0.9	(29.9 ± 1.5) exp 3
V	342 ± 2	456 ± 15	25 ± 1.2	(13.5 ± 0.7) exp 3

6. CONCLUSIONS

Thermal data from Table 1 and Table 2, show that the low power electric furnace will be sufficient to maintain the sample temperature at 300 ^oC, with He or Ar gas, for the present working power (3.5 MW) of IEA-R1 research reactor. For 5 MW, the use of He will be mandatory for 300 ^oC experiments due to excessive GH with Ar gas. CIMAT is versatile device, for multiple samples irradiation at high temperatures (up to 500 °C) with a good temperature stability, mentioned in subsection 4.2.3 including the possibility of in pile electric (resistivity) and magnetic (hysteresis and magnetic after effect) measurements. The noble gas atmosphere of CIMAT, at a pressure of 1.2 bar, hinders the corrosion of the materials at high temperature irradiations and provides additional protection in case of a leakage. The main purpose of CIMAT is to irradiate PV steel AS 508 cl.3 to fluences of 10 exp.19 nvt, simulating the working conditions of the material during approximately 30 years of PWR life time and evaluate quantitavely the irradiation embrittlement, thus establishing methods for the selection of materials more adequate for nuclear technology. The next experimental steps will be: a) measurement of the GH, at 3,5 MW, with He and Ar gases, to be compared with the calculated values of Tables 1 and 2; b) samples irradiation in the IEA-R1 reactor core during 5 months; c) annealing of non-irradiated samples, during the same time period of the irradiation to characterize the thermal effect; d) tensile tests of irradiated and non irradiated samples for final correlation of results. The previous tensile results shown on Table 3 point to a higher toughness of the E samples as compared to V; both have the same nominal composition, but slightly different heat treatments and diverse contents of micro-elements as can be seen in [2]. The ultimate results will make evident the structural changes due to radiation damage and enable the choice of more suitable material for the nuclear environment.

REFERENCES

[1] R.Brosson, G.Lucki, H.Rechemberg, L.Sordi, R.Tiberghien, "Descrição do FORNO GRESIL para Irradiação de Amostras no Reator e Medida de sua Resistência Elétrica" *Publicação IEA n° 212* São Paulo Brasil (1970).

[2] G.Lucki, J.A.Perrotta, A.Kuznetsov, L.F.C.Pedroso de Lima, C.A.A.Teodoro, V.L.R.Salvador, N.A de Pereira, "Caracterização de Aços SA 508 cl.3 para Vasos de Pressão de Reatores PWR" *XII ENFIR Encontro Nacional de Física de Reatores e Termohidráulica,* Rio de Janeiro, October/2000.

[3] G.Lucki, V. Sciani, D.A.Correia, J.A.Perrotta, A.Teixeira e Silva, C.A.Teodoro, "Simulation Technics for Radiation Damage of Materials", *INAC 2002 International Nuclear Atlantic Conference,* Rio de Janeiro August/2002.

[4] H.Etherington, *Nuclear Engineering Handbook,* McGraw Hill Book Co. (1958).

[5] D.A.Costa Correia, *Estudo da Fluência do Aço Inox AISI 316 Irradiado com Neutrons Rápidos e Partículas Alfa,* M.Sc. Thesis presented at IPEN-USP, São Paulo, Brasil.

[6] L.Corwin, *The Use of Small-Scale Specimens for Irradiated Materials STP888*, ASTM, West Conshohoken, USA (1986).

[7] W.R.Corwin, S.T.Rosinski, E. van Walle, *Small Specimen Test Techniques STP 1329,* ASTM, West Conshohoken, USA (1998).