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Procedures for manufacturing an instrumented nuclear fuel element

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ABSTRACT

The IEA-R1 is an open pool research reactor that operated for many years at 2 MW. The reactor uses plate type fuel elements which are formed by assembling eighteen parallel fuel plates. During the years of reactor operation at 2 MW, thermohydraulic safety margins with respect to design limits were always very high. However, more intense oxidation on some external fuel plates was observed when the reactor power was increased to 5 MW. At this new power level, the safety margins are significantly reduced due to the increase of the heat flux on the plates. In order to measure, experimentally, the fuel plate temperature under operation, an instrumented fuel element was constructed to obtain temperature experimental data at various positions of one or more fuel plates in the fuel element. The manufacturing method is characterized by keeping the original fuel element design specifications. Type K stainless sheathed thermocouples are mounted into supports pads in unrestricted positions. During the fuel element assembling, the supports pads with the thermocouples are mechanically fixed by interference between two adjacent fuel plates. The thermocouple wires are directed through the space existing at the bottom of the mounting slot where the fuel plate is fixed to the side plates. The number of thermocouples installed is not restricted and depends only on adaptations that can be made on the mounting slots of the standard fuel element side plates. This work describes the manufacturing procedures for assembling such an instrumented fuel element.

1. Introduction

Research reactors are used primarily for producing radioisotopes and performing materials testing. The plate-type is the most common fuel used in nuclear research reactors, being used in many reactors around the world (Newton et al., 2007; Akyurek and Usman, 2015; Novara et al., 2000; Naka et al., 1999; Chatzidakis et al., 2014; Marin et al., 2004; Maiorino et al., 1998). The fuel element is formed by assembling a number of spaced fuel plates, allowing the passage of a water flow, which is the coolant and moderator as well. Usually, flat and parallel fuel plates compose the fuel element. The main fabrication steps of plate-type fuel elements are the manufacture of fuel plates by rolling and their fixation on two side plates (Cunningham and Boyle, 1955; Kaufman, 1962; Durazzo and Riella, 2015).

The IEA-R1 research reactor of the Nuclear and Energy Research Institute – IPEN/CNEN-SP is an open pool research reactor that operated from 1957 to 1997 at 2 MW (Maiorino et al., 1998). The reactor core consisted of 26 fuel elements and 4 control elements in a 6 × 5 array. Under these operating conditions, the thermohydraulic safety margins with respect to design limits have always been very high.

However, the thermohydraulic analyzes made for a more compact core to operate at 5 MW, composed of 21 fuel elements and 4 control elements, showed that the safety margins are reduced significantly due to the increase of the fuel plates heat flux (Santos et al., 1998). Additionally, after upgrading from 2 to 5 MW, the corrosion rate increased on the external fuel plates of some fuel elements.

For this reason, some doubts appeared concerning the water flow rate values used in the thermohydraulic analyzes. The development of instrumented fuel elements showed up as an important issue in order to obtain experimental data. In a first stage, an instrumented fuel element for measuring pressure and flow rate distribution (Torres et al., 2003) was built. The overall flow rate per fuel element was significantly lower than the estimated value, indicating an elevated bypass flow. Experiments also showed that the flow distribution is not uniform among fuel element channels. The flow rate in the outer channels was 10–15% smaller than the average flow rate in the fuel element, and the flow in the central channel was 8% larger than the average flow (Torres et al., 2003). This fact associated with a high corrosion rate demanded an investigation of the proper fuel element external plates cooling.

The water flow in the channels between two fuel elements is very difficult to be confirmed experimentally. This is not a simple task, since it is an open channel and the flow rate along the channel is not uniformly distributed. The uncertainties for the flow rate determination between fuel assemblies motivated the development of a second

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instrumented fuel element for temperature measurements. This new instrumented fuel element allowed a more realistic safety analysis for the IEA-R1 research reactor and validation of the computer codes as well. This paper describes the procedures for manufacturing such instrumented fuel element and presents operational experience and results.

In general, instrumented fuel elements (IFE) to obtain experimental temperature data are standard fuel assemblies in which instrumented fuel plates are used to have thermocouples attached to the fuel plates by welding. The IFEs for temperature measurement vary in terms of number of instrumented fuel plates, number of thermocouples attached to the fuel plates and diameter of the thermocouples (Kreyger et al., 1970; Boulcourt et al., 2005; Sevdik et al., 2007; Day, 2006).

Kreyger et al. (1970) used three instrumented fuel elements with different uranium loadings to compare measured fuel plate surface temperatures with calculated values. The different instrumented fuel elements were used to simulate the maximum heat flux densities, typical for peripheral and mid-core positions. Ten to twelve Chromel-Alumel thermocouples with stainless steel of 0.34 mm out diameter sheathed wires were used in each instrumented fuel element. Wires were flattened at the hot junction to 0.2 mm, with the flattened length depending on the location of the thermocouple on the fuel plate. The flattened parts of the thermocouple leads were laid in 0.16 mm grooves machined in the aluminium cladding and ultrasonically welded. The unflattened leads were further driven up to the end boxes in small grooves milled along the side plate.

The description of the instrumented fuel element reported by Boulcourt et al. (2005) and Sedvidik et al. (Sevdik et al., 2007) shows that only one instrumented fuel plate containing five Chromel-Alumel thermocouples was used. On the surface of the plates, the thermocouples had a diameter of 0.2 mm. They were inserted into small grooves worked out in the cladding layer of the fuel plate. The thermocouples were then covered with a strip of aluminum and welded. On the side of the fuel plate, the thermocouples had a diameter of 0.34 mm. Above the instrumented fuel element, the diameter of thermocouples was 1 mm. Then, the thermocouples were connected to the data acquisition system (Boulcourt et al., 2005).

Day (2006) used an instrumented fuel element with thermocouples attached to different positions in various fuel plates. Thermocouples with diameter of 0.25 mm were fixed in the fuel plates in three different ways. In the first, the thermocouple was inserted and welded into the meat of the fuel plate. In the second, the thermocouple was fixed just below the surface of the fuel plate, also by welding. In the third way, the thermocouple was attached to the surface of the fuel plate by spot welding.

The instrumented fuel elements described in the literature have in common the use of welding of the thermocouples in the fuel plate. In this technique, it is usual the opening of a groove on the surface of the fuel plate by milling. The thermocouples are housed into the groove and fixed by welding. The thermocouple is then driven to the outer end of the fuel element and connected to a data acquisition system.

The usual technique for attaching the thermocouple on the fuel plate has the important disadvantage of requiring that a groove be milled at the surface of the fuel plate. The aluminum cladding layer of the fuel plate ensures the tightness and protection of the fuel meat where nuclear fission occurs. The cladding usually has thickness ranging between 0.25 and 0.38 mm, so it is very thin. The milling of grooves removes cladding material. Therefore, a layer of 0.20 mm is removed from the cladding of the fuel plate, which dangerously reduces its thickness.

On design of fuel plate, the cladding thickness is specified to ensure the physical protection of the fuel meat against the mechanical action of external agents (scratches and marks) and against wear due to corrosion phenomena. The effective decrease in thickness in the cladding of instrumented fuel plates at the places where thermocouples are fixed infringes the project assumptions. Aluminum and stainless steel junction forms a galvanic pair, which might increase the local corrosion rate and could cause cladding failures. As a result, the reliability and lifetime of the instrumented fuel plate, as well as the fuel element as a whole, are compromised.

In addition, the thermocouple junction, which has a diameter of 0.34 mm, must be flattened until the thickness is reduced to around 0.16 mm to fit in the groove (Kreyger et al., 1970). This operation together with the welding stresses the thermocouple junction, resulting in its failure. Kreyger et al. (1970) mention the failure of ten thermocouples for thirty-four thermocouples installed.

Another disadvantage observed in instrumented fuel elements described in the literature is how thermocouples wires are driven to the outside of instrumented fuel element. Channels are milled along the side plates, so that the thermocouples are housed therein. This method does not fully protect the thermocouples from mechanical stresses arising from the coolant water flow.

This paper describes the manufacturing of an instrumented fuel element for temperature measurements where the thermocouples are not fixed by milled grooves on the surface of the fuel plates and subsequent welding. Therefore, the integrity of the cladding and the originality of the fuel plate design are preserved. By using special support pads, the thermocouples are mechanically fixed between adjacent fuel plates. The thermocouples are driven to the outside in such a way that they are fully isolated and protected from mechanical stresses caused by the water flow through the fuel element cooling channels. Thermocouples use the space between the edge of the fuel plate and the bottom of the slot in which the fuel plate is fitted and mechanically spiked. Therefore, thermocouples remain insulated and protected inside the slot in which the fuel plate is mounted.

2. General procedures for manufacturing a standard fuel element

Research reactor fuel elements have many different shapes and sizes, but they have features in common. The fuel material is contained in fuel plates, which are assembled on side plates and attached by roll swaging. The fuel elements have nozzles to fit the reactor matrix plate. The main components are two side plates, typically eighteen to twenty fuel plates, one nozzle and one handling pin, as showed in Fig. 1.

The fuel plates are manufactured by adopting the traditional assembling technique of a fuel meat inserted in an aluminum frame and cladded with aluminum plates, which are bonded with subsequent rolling. This technique is known internationally by "picture-frame technique" (Cunningham and Boyle, 1955; Kaufman, 1962; Durazzo and Riella, 2015) and adopts assembling and rolling of a set composed by the fuel meat, an aluminum frame plate and two aluminum cladding plates. In this way, after the rolling operation, it is fabricated a fuel plate containing the fuel meat totally isolated from the environment, which is done through the perfect metallurgical bonding between the meat and frame with the claddings. Fig. 2 illustrates the procedure of preparing the assemblies for rolling.

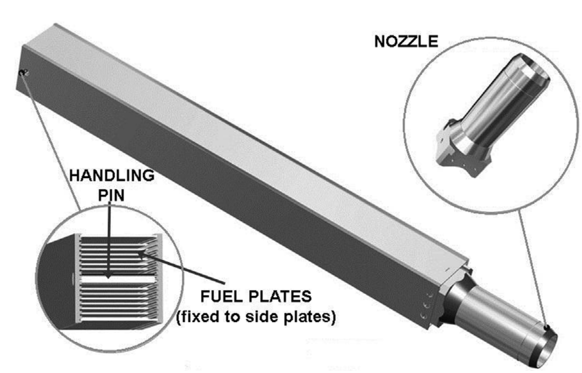

Fig. 1. Schematic illustration of a typical fuel element.

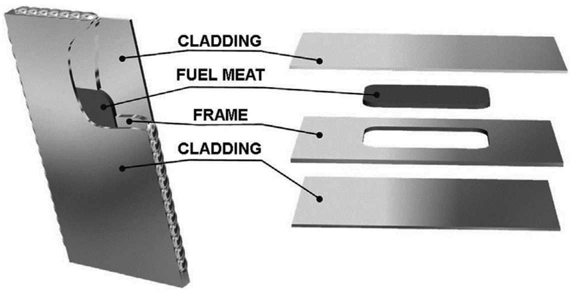

Fig. 2. Diagram illustrating the assembling of the set fuel meat-frame-claddings.

Powder metallurgy techniques are used in manufacturing the meats containing uranium powder compounds enriched to 20% in the ^{235}U isotope (nuclear fuel material) together with aluminum powder (structural material of the meat). Uranium silicide U_3Si_2 powder is the most common material used as fissile. The uranium-molybdenum alloys have been studied to replace the U_3Si_2, which will permit increasing the fuel uranium density within high performance research reactors.

The hot rolling is performed in several passes following a well-established rolling schedule. In the cold rolling operation, the specified thicknesses for the fuel plate, claddings and fuel meat are achieved. Fig. 3 shows the fuel plate, illustrating its fuel meat.

After its fabrication, the fuel plates are mounted to form the structural body of the fuel element. The plates are fixed to two side plates by mechanical swaging. Subsequently, the nozzle is fixed. A handling pin is fixed on the side plates at the nozzle opposite position.

The side plates are made from aluminum strips that are machined to specified thickness. Then, slots are milled on the side plates. The slots support the fuel plates during their mechanical fixing to the side plates. There are small grooves at the side of the main slots to help the positioning of the roll swaging wheel, as illustrated in Fig. 4. The side plates are generally made with 6061-T6 aluminum.

The two side plates are installed in the roll swaging fixture against stops so they line up longitudinally. The side plates are then locked using clamps located on top of the holding fixture. The bed of the roll swaging fixture can be a lathe or a milling machine. Fig. 5 shows an example of a roll swaging fixture mounted in a lathe. The roll swaging head is attached to the gantry of the lathe and the bed traverses under it.

Fuel plates assembling are carried out from the bottom upwards. The first fuel plate is slid into position inside the main slot. Isopropyl alcohol is used as lubricant. The wheel width is adjusted to penetrate indo side plate auxiliary groove over the main slot. The swaging wheel is positioned at the extremity of the fuel plate and is moved to the opposite extremity, deforming the auxiliary groove by the application of a controlled predetermined force. By running the roll swaging wheel through the groove, the fuel plate is stuck on the side plate (see Fig. 4). After, the other side of the fuel plate is roll swaged.

The side-plate holding fixture must be strong enough to keep the side plates in place under the swaging tension. Fig. 6 shows the side plates locked in place and a fuel assembly partially complete.

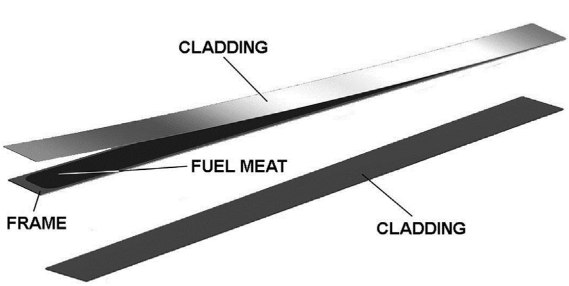

Fig. 3. Schematic illustration of the finished fuel plate after rolling.

The nozzle can be attached with screws or by welding. Welding provides the most rigid structure, but the nozzle and fuel element should be rigidly aligned and the weld should be programmed to minimize distortion. If screws are used, they need to be peened to ensure that they do not loosen as a result of reactor vibration. The handling pin is installed by riveting. The fuel element is identified by engraving an identifying mark (letters or/and numbers) on the side plates.

3. Procedures for manufacturing the instrumented fuel element (IFE)

The IEA-R1 research reactor is classified among the Material Testing Reactor (MTR) type. Since the reactor upgrade to 5 MW, the core consists of 20 fuel assemblies, each with 18 fuel plates mounted on two side plates forming 17 independent closed flow channels. Fig. 7 shows a typical arrangement of the fuel elements, reflectors, control rods and irradiation positions inside the reactor core. The core is mounted in a 5 × 5 array formed by 20 fuel elements, 4 control fuel elements and a central irradiation device. Table 1 summarizes the main design parameters of the IEA-R1 research reactor.

The IFE has been designed to keep, as much as possible, the design of the standard fuel element components. Therefore, the specifications for the fuel and the side plates of the IFE are identical to those referring to the standard fuel element. The objective is to provide a method which enables the manufacture of an IFE without changing the fuel element specifications and preserving the surface quality of the fuel plates. Maintaining the original specifications of the fuel plate design guarantees the performance, reliability and durability.

Thermocouples were fixed mechanically on the fuel plate during assembly of a standard fuel element by means of special holders, known as “support pads”, while keeping the cladding thickness of the fuel plate. The thermocouples were driven to the outside of the fuel element through their accommodation into the gap between the edge of the fuel plate and the bottom of the slot in which the fuel plate is inserted and fixed to the side plates. This ensures thermocouples isolation from the water flowing through the cooling channel between two adjacent fuel plates.

Three IFE channels were monitored: the central channel and the last two more external channels, formed by the external fuel plates. Fourteen thermocouples were installed. Fig. 8 shows a section of the IFE where the positions of the thermocouples are indicated. Three types of thermocouples were used (TC, TC/TF and TF), as follows; TC for measuring temperature on the surface of the fuel plate, TC/TF for measuring temperature on the surface of the fuel plate and water in the cooling channel, and TF for measuring inlet and outlet water temperature. Each of the channels was monitored by three thermocouples located in different axial positions of the IFE (TC type thermocouples). In the lower region of the IFE, three thermocouples (one in each channel) were also installed to measure the water temperature inside the channel (TC/TF type thermocouples). Two thermocouples were installed before and after the active zone of the IFE in order to measure the inlet and outlet water temperatures (TF type thermocouples).

All the thermocouples are K type, made of stainless steel sheathed wires with 0.50 mm out diameter. The error is less than 0.5 °C for temperatures lower than 50 °C, and less than 0.8 °C for temperatures between 50 °C and 100 °C.

Fig. 9 shows a scheme of the thermocouple holder, or support pad, in which one or more thermocouple wires are mechanically fixed. The support pad has diameter of 10 mm with a reduction of 15.42% of the local flow area. However, this reduction is not significant regarding local pressure and flow in the channel. Besides, smaller diameters support pads reduce this effect.

Small holes are machined in the support pad, denominated housing holes, in which thermocouple wires are inserted. The thermocouple

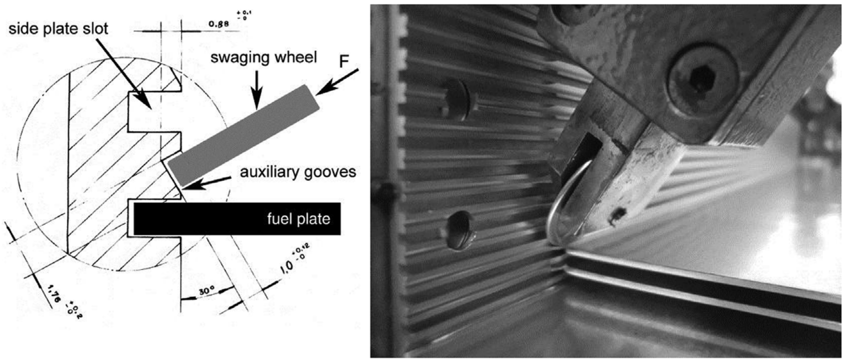

Fig. 4. Details of the roll swaging operation.

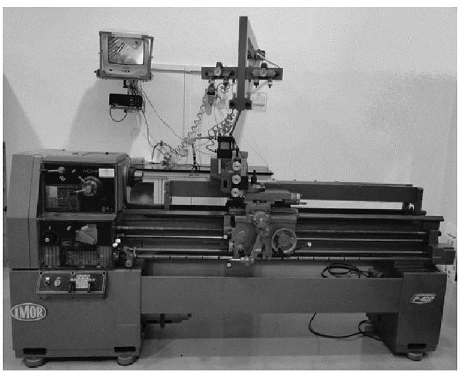

Fig. 5. Typical roll swaging fixture mounted in a lathe.

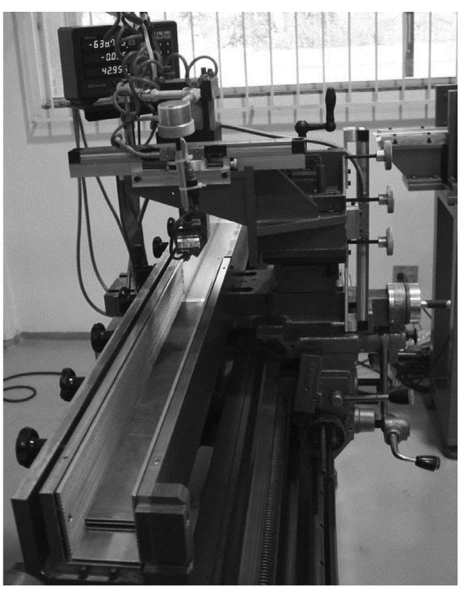

Fig. 6. Details of the side plates positioning in the roll swaging bed.

wire has a diameter of 0.50 mm and the housing hole has a slightly larger diameter of 0.55 mm.

A variable number of thermocouple wires can be mounted on the same support pad, in different positions. Fig. 9 shows a scheme of a support pad on which was mounted two thermocouple wires in different positions (TC/TF). In position "A", the thermocouple measures the average surface temperature of two adjacent fuel plates. In this position, the thermocouple wire is fixed at the center of the thickness of the support pad, which is in contact with the surface of two adjacent fuel plates. If desired, the position "A" can be displaced to a distance the nearest to the surface of the support pad that is in contact with the surface of the fuel plate whose temperature is to be measured, for example 0.05 mm. In position "B", the thermocouple passes through the support pad and is fixed, so that its junction is in contact with cooling water flowing between two adjacent fuel plates.

The thermocouple wires were fixed in the support pad by plastic deformation due to pressure action. The thermocouple wires are introduced and positioned inside the housing holes. Then, the support pad is subjected to compression pressure and is deformed plastically until its thickness is decreased in 0.10 mm, locking the thermocouple wires in place.

The height of the support pad after the deformation for mounting the thermocouples was defined based on the maximum width specified for the cooling channel, i.e. the maximum distance specified between two adjacent fuel plates. In general, the support pad height must be 0.10 mm greater than this value. This allows the mechanical fixation of the support pads between adjacent fuel plates by using interference, as shown in Fig. 10. For the IFE, the support pad with the thermocouples is 2.99 mm in height. The support pad has rounded corners to avoid damages to the surface of the fuel plates that will be in contact with it during the assembling. The material of the support pads is the same material used for the cladding of the fuel plates, i.e. aluminum alloy 6061.

A length of 20 mm was withdrawn from the slot edge where the fuel plate is fixed. This opening, or "window", was used for driving the thermocouple wires out of the IFE through the slot of the side plate. The "window" is machined in the side plate at the same longitudinal position where the support pad is attached. Fig. 11 illustrates the positioning of a support pad and the thermocouples wires path through the window at the bottom of the slot. The thermocouple wires are driven out through the space between the bottom of the slot and the fuel plate edge. This is done before the fuel plate is fixed to the side plates. Once the thermocouple wires are positioned at the bottom of the slot, they go through the entire longitudinal length of the channel.

The fuel plate into which the temperature is to be measured is inserted into its respective mounting slot and is mechanically fixed in the side plate by plastic deformation of the auxiliary groove by the action of the roller stamping wheel (see Fig. 4).

A polyethylene strip is used for positioning one or more support pads. This strip is used for keeping the support pad in place while the upper fuel plate is fixed to the side plates. Once the support pad is positioned over the fuel plate, the adjacent fuel plate is inserted in its respective slot and is mechanically fixed (see Fig. 4).

Then, the support pad is mechanically fixed between the two adjacent fuel plates by means of negative interference of 0.10 mm, as illustrated in Fig. 10. After the attachment of the adjacent fuel plate, the positioning strip is removed by means of its displacement in the lateral direction in order to be released from the notch used to hold the support pad in place. Fig. 12 illustrates the use of the positioning strip.

Although 14 thermocouples were installed, the maximum number

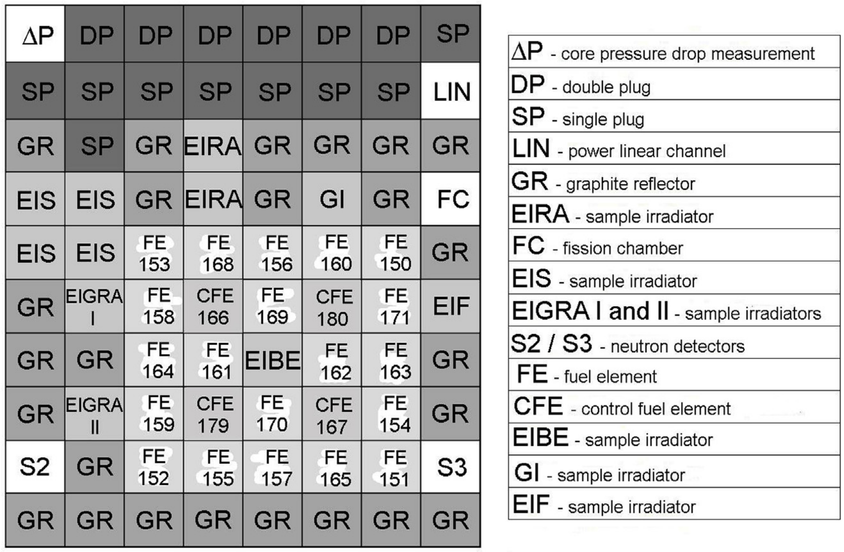

Fig. 7. Typical arrangement of the IAE-R1 research reactor core.

Table 1
Description of the IEA-R1 research reactor design parameters.

steady state power level	5 MW	
fuel		
fuel enrichment	< 19.75%	
N° of fuel element in core	24	
standard fuel element	20	
control fuel element	4	
fuel type	U_3O_8–Al	density 2.3 gU/cm^3 mass U_3O_8 per fuel element 1254.1 g mass ^{235}U per fuel element 196.9 g
	U_3Si_2–Al	density 3.0 gU/cm^3 mass U_3Si_2 per fuel element 1517.3 g mass ^{235}U per fuel element 275.5 g
Max. inlet temperature	40 °C	
Temperature Diff. at 5 MW	5.8 °C	Between inlet and outlet
N° of fuel plates in		
Standard fuel element	18	
Control fuel element	12	
thickness of the plates		
fuel	0.76 mm	
clad	0.38 mm	
total thickness	1.52 mm	
total width of the plates	67.1 mm	
fuel meat dimensions	0.76 × 62.6 × 600	thickness x width x height (mm)
thickness of water channel	2.89 mm	
coolant flow rate		
total	772	m^3/h
fuel element	22.8 × 24 = 547.2	m^3/h
bypass	224.8	m^3/h
core pressure drop	7835 kPa	
clad temperature (max.)	95 °C	

of thermocouple is not restrictive, since it depends only on the dimensions of the gap between the edge of the fuel plate and the bottom of the mounting slot. The gap dimensions, or depth of the mounting slot through which the thermocouple wires are driven, are flexible and can be adapted to a bigger number of thermocouples in the side plate design. Fig. 13 illustrates a support pad positioned in place between two adjacent fuel plates.

The thermocouple wires are directed to the top of the IFE and are docked and grouped into a fixing device which is attached by bolts on the side plate, inside the top end of the IFE, as illustrated in Fig. 14. In addition to the thermocouples attached to the support pads, two thermocouples were installed at inlet and outlet of the IFE for measuring the water temperature. Fig. 15A and Fig. 15B illustrate these thermocouples (TF1 and TF14), respectively. For the sake of protection and organization, all thermocouples are guided out of the pool through a flexible stainless steel tubing. A removable clamp fixes the device to the flexible tubing.

The basic manufacturing procedures developed in this work are applicable regardless of the fuel element specifications for use in any research reactor using flat plates. The maximum number of thermocouples and instrumented fuel plates will depend on the instrumented fuel element design, particularly the maximum depth allowed for mounting slot through which the thermocouple wires will pass through. It depends also on the capacity of the stainless steel flexible tubing that will lead the thermocouples out of the instrumented fuel element. As the depth of the mounting slot is flexible and both channels at the right and left side plates can be used for driving out thermocouple wires, the number of thermocouples installed in the same fuel plate is virtually unrestricted. Fig. 16 illustrates the instrumented fuel element fabricated according to the manufacturing procedures described in this work.

4. Operation experience

As the focus of this paper is on the instrumented fuel element fabrication, a description of the operation experience is presented very briefly, just to illustrate the IFE importance in the thermohydraulic experiments.

The IFE has been operating without problems since 2010 and currently has a burnup of 32%. During this time, two visual inspections were performed with the help of an underwater camera. Despite of the number of experiments (Hainoun et al., 2014; Umbehaun et al., 2015; Maprelian et al., 2015), no problems were detected, attesting its good performance.

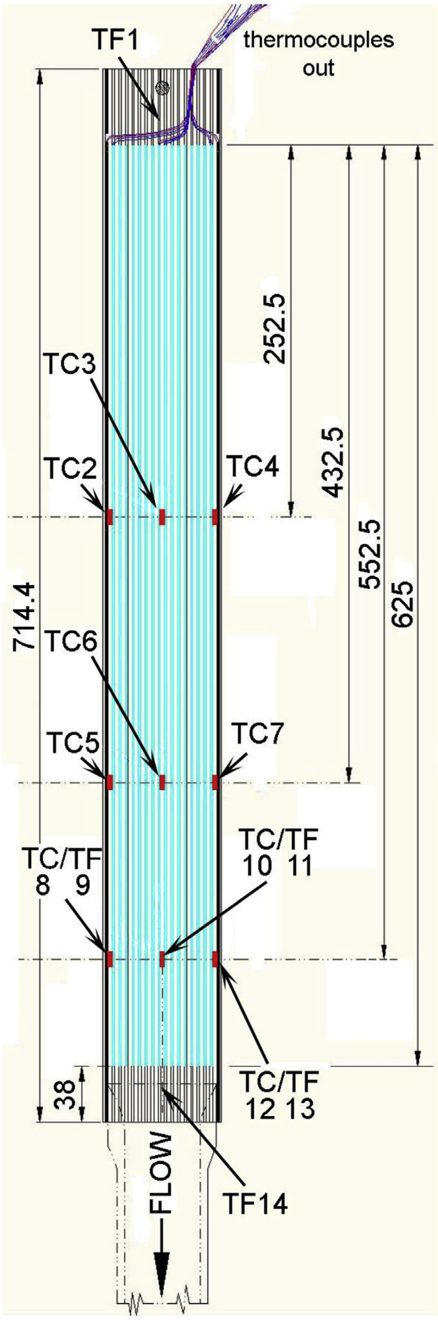

Fig. 8. Section of the IFE showing the thermocouple positions.

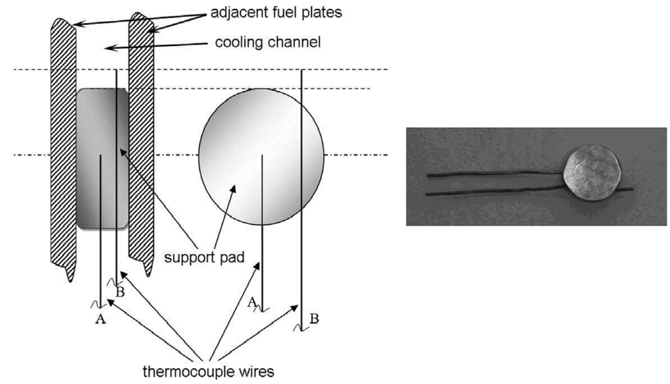

Fig. 9. Scheme and photography of a support pad with two thermocouples (TC/TF type).

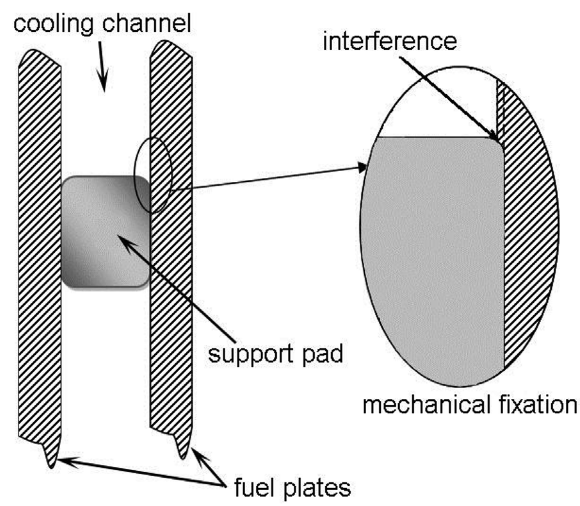

Fig. 10. Fixation of the support pad between adjacent fuel plates.

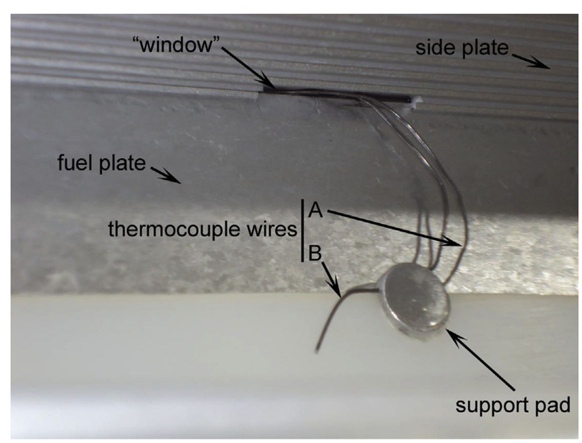

Fig. 11. Illustration of extracting thermocouple wires through the "window".

IFE results supported an IAEA Coordination Research Project-CRP (IAEA CRP 1496 - "Innovative methods in Research Reactor Analysis: Benchmark against Experimental Data on Neutronics and Thermal Hydraulic Computational Methods and Tools for Operation and Safety Analysis of Research Reactors") (Hainoun et al., 2014). This CRP focused on benchmarking against experimental data on neutronic and thermohydraulic computational methods and tools, which are routinely utilized for operation and safety analysis of research reactors. The experimental results were compared with the calculations performed with four different thermohydraulic codes used by independent teams of six countries (Hainoun et al., 2014).

The IFE results allowed useful evaluations of the calculations. Fig. 17 shows a comparison between the evolution of the fuel plate surface temperature from different codes and experimental IFE results for loss of flow accident (LOFA) event. IFE design improvements to decrease the thermal resistance in the contact (Hainoun et al., 2014) were suggested, mainly related to the contact between the support pad and the surface of the fuel plate.

IEA-R1 reactor simulation experiments demonstrated a good IFE performance (Umbehaun et al., 2015). Fig. 18 shows the results obtained in an experiment composed of the following steps:

(1) With the reactor off, pump was started up to the nominal flow rate.
(2) Reactor was started up.

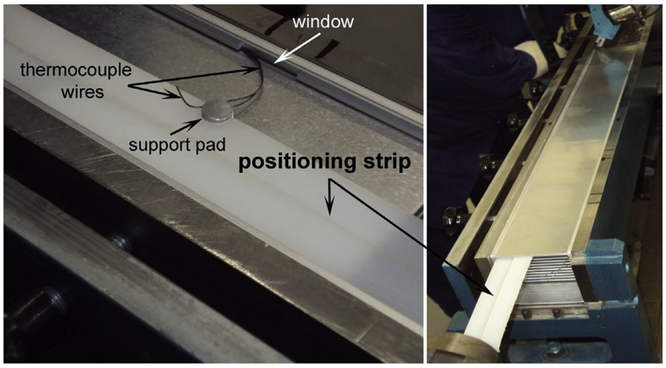

Fig. 12. Illustration of the positioning strip.

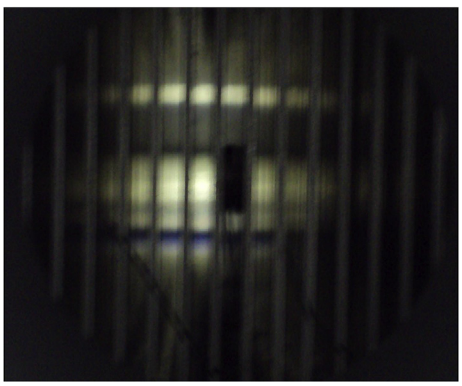

Fig. 13. Illustration of support pad between adjacent fuel plates.

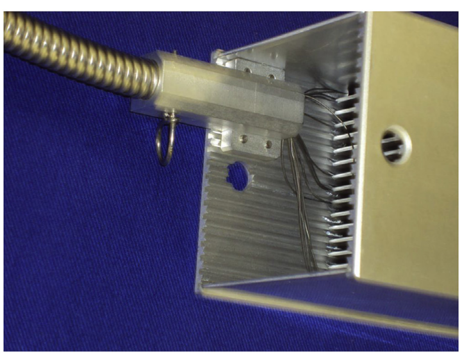

Fig. 14. Illustration of the thermocouples wires path.

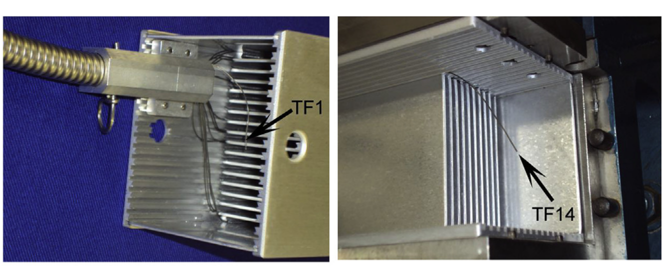

Fig. 15. Illustration of the additional thermocouples wires.

(3) Reactor power was stabilized at 3.5 MW, 4.0 MW, 4.5 MW and 5.0 MW.
(4) Reactor power was reduced in steps and operated at the following powers: 3.5 MW, 3.0 MW, 2.0 MW and 1.0 MW.
(5) Reactor power was increased to 3.5 MW, and after stabilization at this power, pump was turned off.

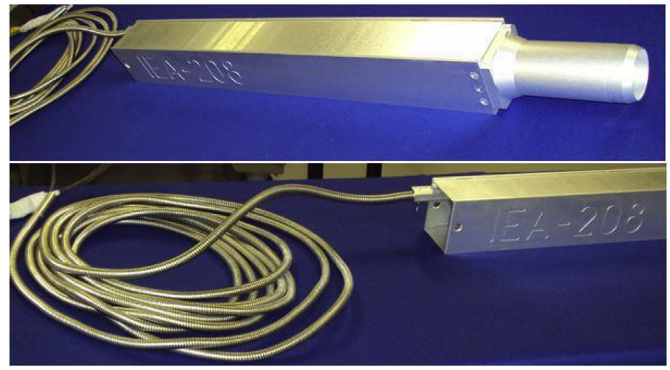

Fig. 16. Views of the finished instrumented fuel element.

Recently, a test section for experimental simulation of loss of coolant accident (STAR) was developed to operate in the pool of the IEA-R1 research reactor (Maprelian et al., 2015). This test section will provide experimental data on partial and total uncovering of the IFE. Experimental results will be useful for validation of computer codes, particularly on heat removal efficiency aspects (safety function) in accident conditions. STAR comprises a base on which is installed the IFE, a cylindrical stainless steel hull, a compressed air system for the test section emptying and refilling, and an instrumentation for temperature and level measurements. The commissioning tests, or pre-operational check, consisted of several preliminary tests to verify experimental procedures; difficulties during assembling of STAR in the pool; difficulties in controlling the velocity of emptying and refilling; repeatability capacity; tests of equipment; valves and systems and tests of instrumentation and data acquisition system. The STAR section was assembled and installed in the pool of IEA-R1 reactor successfully.

5. Conclusions

The instrumented fuel element described in this paper showed to be a very useful tool for measuring temperatures providing important information for the thermohydraulic analyzes.

The developed IFE presented a great flexibility in terms of thermocouples installation. Temperatures can be measured during steady state and transient operation of the research reactor.

The IFE presented in this work has unique features and advantages, since the adopted manufacturing method preserves the fuel plate original design, with consequent increase of the reliability and lifetime. The IFE has a higher robustness since thermocouples can have a larger diameter, and thus greater mechanical strength, besides being less susceptible to failures resulting from the welding process usually adopted in the manufacturing of instrumented fuel elements. Furthermore, thermocouples remain protected from mechanical actions throughout their path out of the IFE, thus minimizing the possibility of failures.

The IFE has been operating in the IEA-R1 research reactor for more than seven years, reaching 32% burnup without any type of failure. It provided temperature information during reactor operation in innumerous experiments to date. Experiments using the IFE simulating loss of coolant accident (LOCA) are in progress.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://

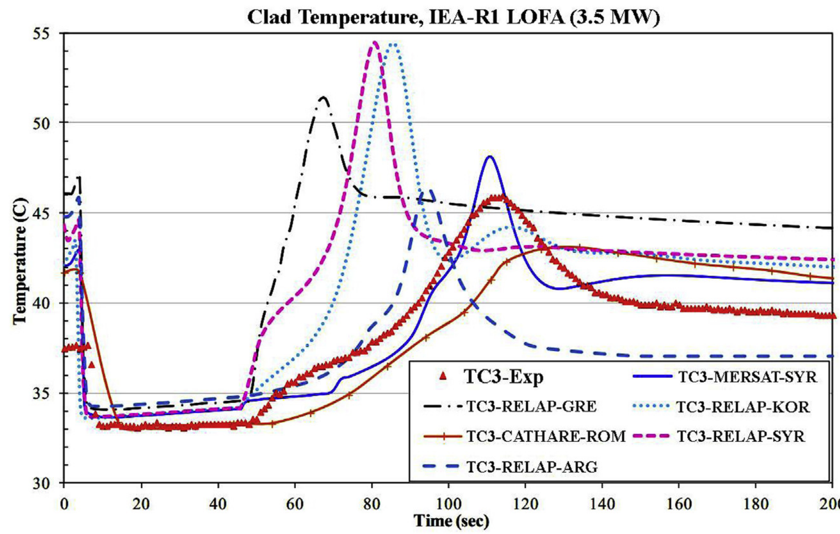

Fig. 17. Clad temperatures at 252.5 mm (TC3) (Hainoun et al., 2014).

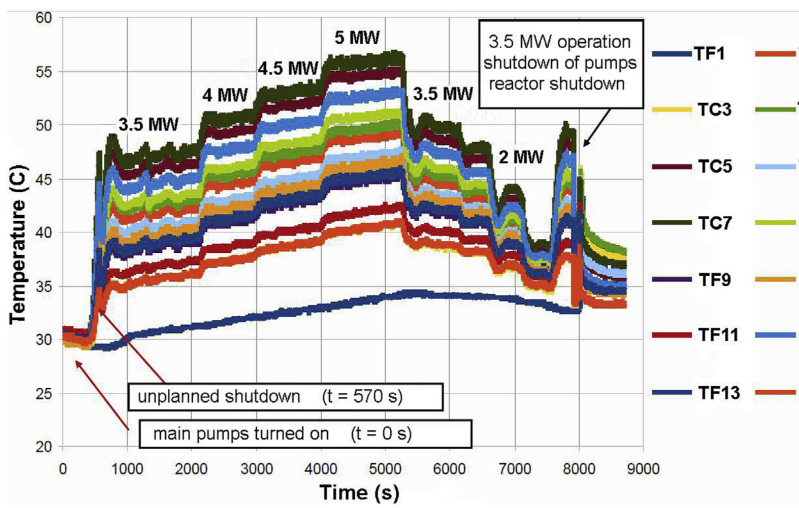

Fig. 18. Experimental results for IFE in the IEA-R1 reactor (Umbehaun et al., 2015).

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