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INSTRUMENTED FUEL ELEMENT RECOVERY IN IPR-R1 TRIGA NUCLEAR RESEARCH REACTOR

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Abstract. *The IPR-R1 TRIGA Mark-I research reactor at the Nuclear Technology Development Center - CDTN (Belo Horizonte) reached its first criticality on November 1960, with a core configuration containing 56 aluminum clad standard TRIGA fuel elements and a maximum thermal power of 30 kW. Since the middles of the 60's decade the General Atomics, supplier of the TRIGA reactor, discontinued the fabrication of such aluminum clad fuel elements. In order to upgrade the IPR-R1 reactor power, nine stainless steel clad fuel elements were purchased in 1971. One of these fuel elements was instrumented in the centerline with three type K thermocouples. On December 2000, four of these stainless steel clad fuel elements were placed into the core allowing to uprate the nominal power to 250 kW steady state. In 2004 the instrumented fuel element (IF) was inserted into the core hottest position, predicted by neutronic calculations. The IF stayed in this position up to 2007, allowing heat transfer investigations in several operating powers, including the maximum power of 250 kW. During this time it also monitored the core temperature in all operations. The fuel temperature and other operational parameters were stored in a computer hard disk, with an accessible historical database, in order to make the chronological information on reactor performance and its behavior available to users. After almost 3 years of monitoring the core temperature, it was noticed that one of the three thermocouples didn't send anymore the correct value of the measures. Later on, the other two thermocouples also failed in its measures. It was observed the rupture of the thermocouples in the connector placed between the thermoelements wire and its extension cables. This paper describes the methodology used in the recovery of the instrumented fuel element thermocouples, carried out in October of 2008 at CDTN. It was obtained partial success in the restoration of the thermoelements continuity. There are suggested procedures for new recovery and the returning of the IF to the core, improving the operational safety to the reactor. According to the specification of General Atomics Electronic Systems Inc instrumentation, and like several TRIGA reactors in operation today, it is recommended the existence of at least two instrumented fuel elements in the core. The core temperature monitoring in all the operations, is a recommendation of the International Atomic Energy Agency (IAEA), and this parameter is the main operational limit of a nuclear reactor. The core temperature monitoring was adopted in the IPR-R1 TRIGA Safety Analysis Report as safety operational limit and can not exceed 550 ^{o}C.*

Keywords: *TRIGA Reactor; research nuclear reactor; thermocouples; instrumented fuel element; temperature.*

1. INTRODUCTION

The instrumented fuel element (IF), showed in Fig. 1, is in all aspects identical to standard fuel elements, except that it is equipped with three chromel-alumel thermocouples (K type), embedded in the fuel meat. The sensitive tips of the thermocouples are located in the centerline of the fuel element. Their axial positions are one at the half-height of the fuel meat and the other two 2.54 mm above and 2.54 mm below. The IF was purchased in 1971 and placed in the IPR-R1 reactor core on 08.18.2004 and stayed there until July, 2007. During this time it monitored the hottest core temperature in all reactor operations and it also allowed heat transfer investigations to the reactor upgrade power of 100 kW to 250 kW (Mesquita, 2005). After about 3 years monitoring the core temperature at the core hottest position, the three thermocouples failed in its measures because the rupture in the connector placed between the thermocouples wire and its extension cables (Fig. 2). On August 2007, the instrumented fuel element was removed from the core and placed in a rack located in the reactor tank inner wall (immersed in the pool water). One year later the IF was removed of the TRIGA pool and put in a well for irradiated fuel storage, filled with water, located at the reactor room. On October 2008, the IF was raised and it was started the work to recover the thermocouples continuity. The works were concluded with partial success on 10.17.2008.

This paper describes the ongoing research project at CDTN, supported by *Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG)*, that has the objective to repair the instrumented fuel element of the IPR-R1 TRIGA reactor (Mesquita, 2008). The project will improve the execution of neutronic and thermal-hydraulic experiments, foreseen in the CDTN research program. The thermocouple tip is in the center of the fuel element, where the temperature is normally the highest and with the instrumented fuel elements inserted in the locations with maximum power density (the hottest position in the core) it provides protection to the reactor and contributes to the operational safety of the facility. Figure 1 shows the IF before and after its positioning in the IPR-R1 reactor core.

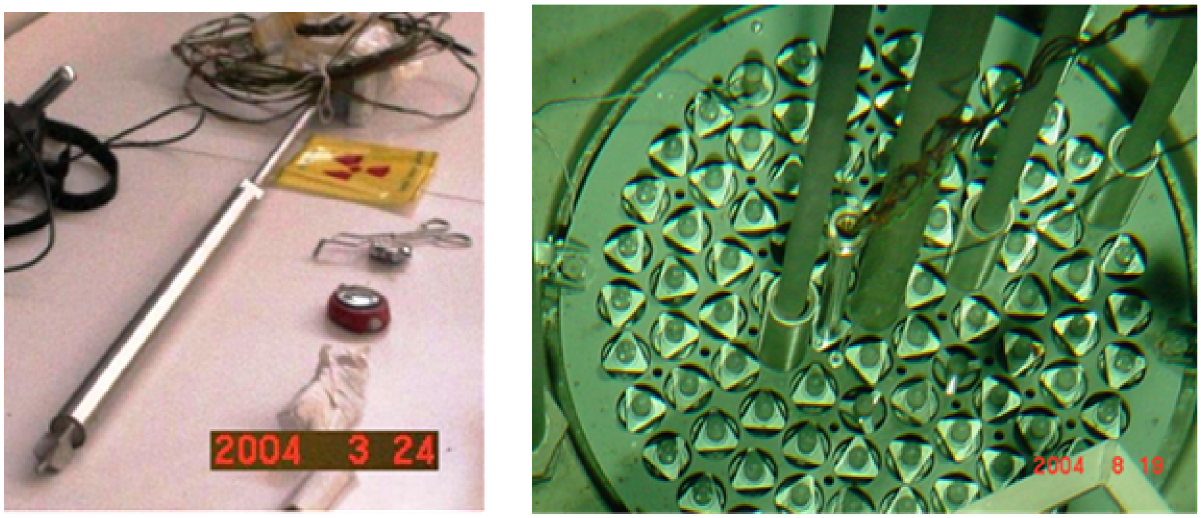

Figure 1. Instrumented fuel element before and after its positioning in the IPR-R1 reactor core.

2. INSTRUMENTED FUEL ELEMENT DESCRIPTION AND THE THERMOCOUPLES BREAKDOWN

The TRIGA reactor's fuel element is a cylindrical rod with stainless steel (SS-304) cladding. Its total length is approximately 721 mm with 38.1 mm diameter. Fuel material in each element is 381 mm long. There are 88.1 mm long cylindrical graphite slugs at the top and bottom ends, which act as neutron axial reflectors. In the center of the fuel material there is a 6.35 mm diameter hole which is filled by a zirconium rod. The fuel is a homogeneous mixture of uranium and zirconium hydride. Standard stainless steel-clad fuel elements with 12 wt % uranium of 20% enrichment (uranium is 20 wt % ^{235}U). The instrumented fuel element (IF) has the same nuclear characteristics of the normal fuel element but posses three type K (chromel-alumel) thermocouples embedded in its zirconium centerline pin. The IF geometry and dimensions are shown in Fig. 3. The Figure 4 shows the place of the thermocouples breakdown. The thermocouples are manufactured with compacted magnesium oxide (MgO) insulation housed in a stainless steel sheath with 1.0 mm diameter that protects the thermocouple element from the environment. The thermocouples wires have 0.14 mm of diameter (General Gulf Atomic, 1971). The thermocouples leave the zirconium centerline pin, pass for the graphite reflector, cross the spacer and leave the IF. Approximately at 10 cm of this point exists the connection of the chromel-alumel wires and the extension wires, also made of chromel-alumel (detail of Fig. 4). The rupture occurred in this connector as shown in the photograph of Figure 2. Analyzing the contact place, it could be concluded that the thermoelements wires had been put in contact with two extension wires without weld and only protected by Epoxy® resin inside one potting sleeve of plastic material (General Gulf Atomic, 1972). Possibly, due to the high nuclear radiation it deteriorated the resin and stopped the electrical and mechanical contact between the wires.

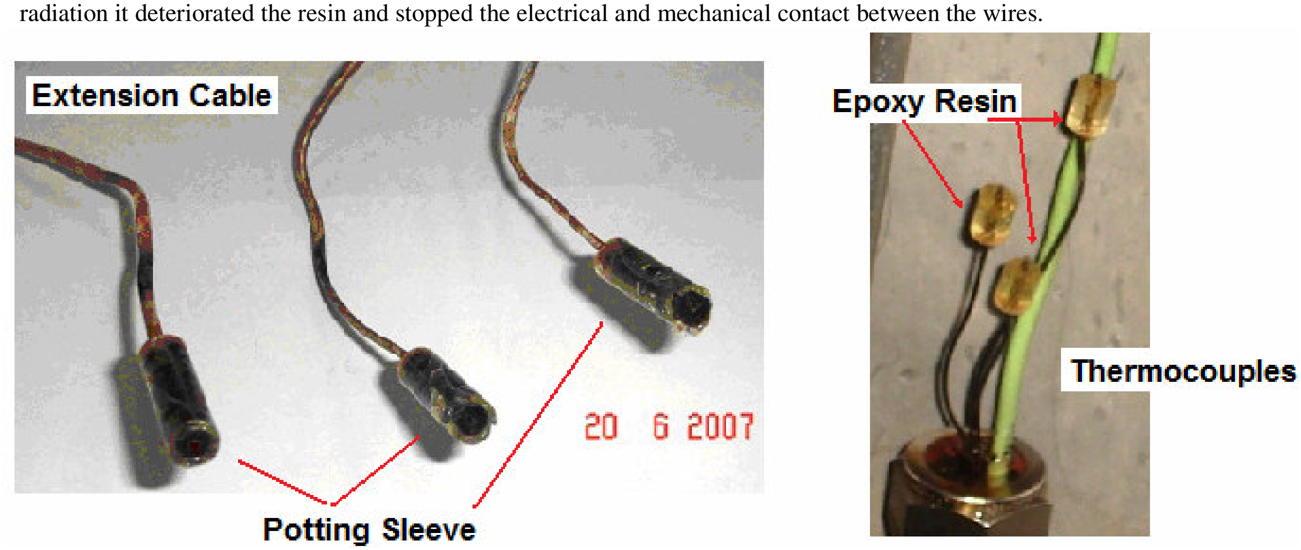

Figure 2. The thermocouples and extension cables after the breakdown

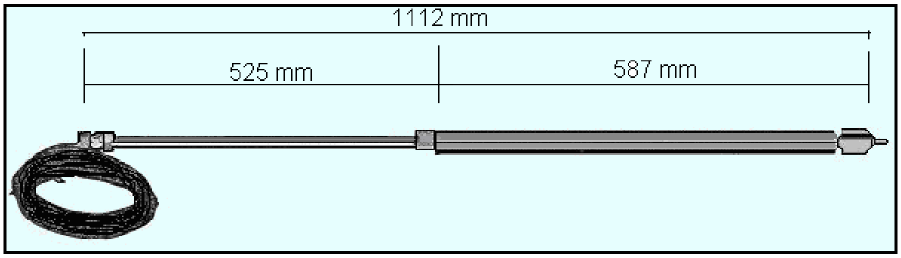

Figure 3. Instrumented fuel element (serial number 6821TC)

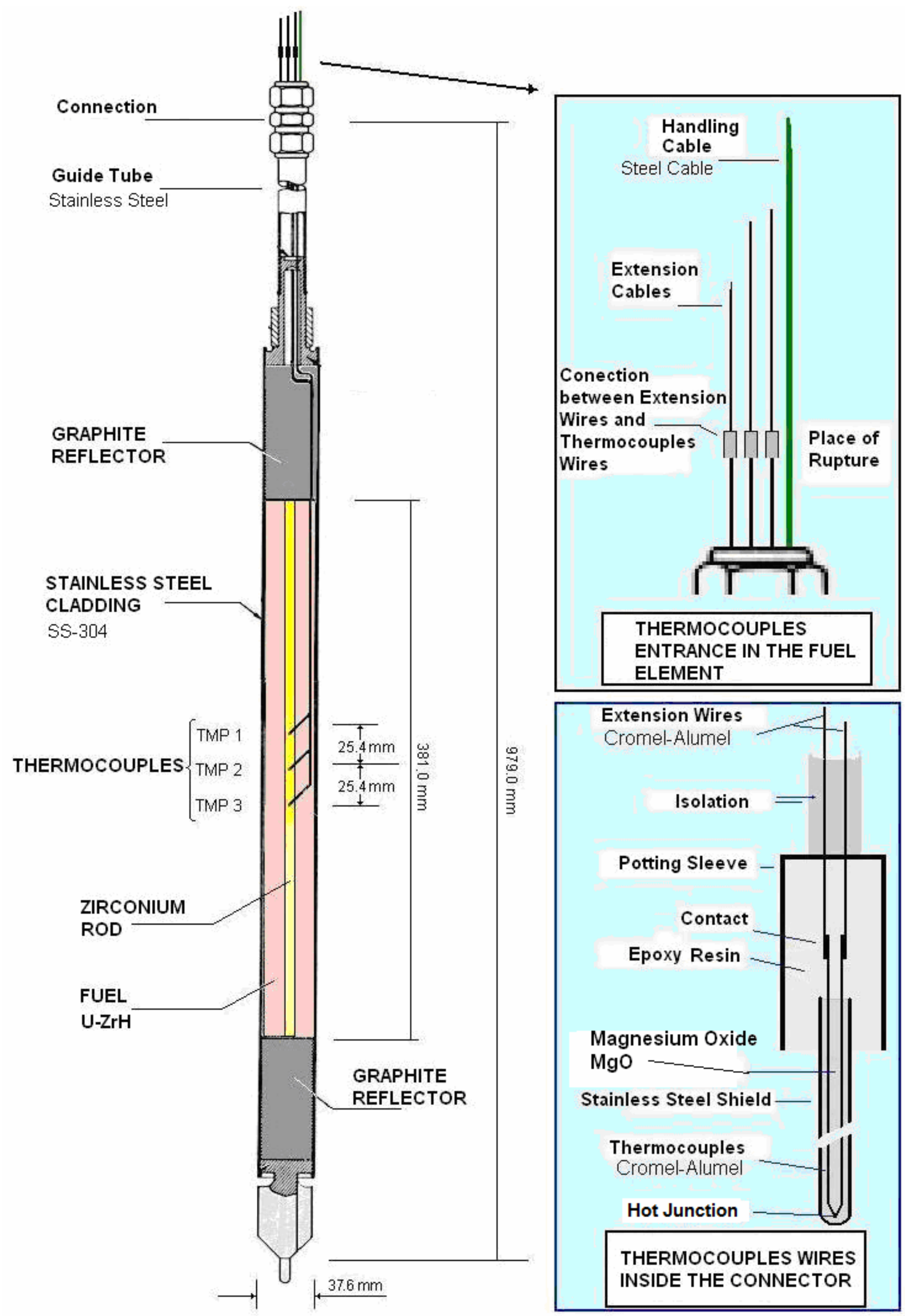

Figure 4. Instrumented fuel element and thermocouple connector detail

3. INSTRUMENTED FUEL BURNUP CALCULATION RESULTS

The results of the Monte Carlo burnup calculations for the instrumented fuel element carried out by Dalle (2009) are presented. The neutronic analyses were performed by using the MCNP, ORIGEN and MONTEBURNS codes, considering the instrumented fuel element located in the core hottest position and the core total released energy of 100.2 MWh. The simulations results are shown in the Table 1 and Table 2. The IF had a burnup of 0.2 g of ^{235}U (about 0.5%).

The analysis of radioactive decay of the IF was conservative, because it was disregarded all the decay occurred during the time that the IF was in reactor core. The IF spent almost 3 years in reactor core and only about 42 days of this period was irradiation (reactor critical), all the remaining was decay time, which was not taken into account in the analysis. The calculations show that one year after withdrawing the IF from the core, the fuel activity was slightly higher than 1 Ci and the decay heat is less than 1 mW and the parameters of radiotoxicity by ingestion and inhalation are within the expected range.

Table 1. Burnup calculated results for instrumented fuel element using the MONTEBURNS code (Dalle, 2009).

Decay time (month)	^{235}U Mass* (g)	Activity (Ci)	Decay Heat (mW)	Radiotoxicity by Inhalation (m^3 of air)	Radiotoxicity by Ingestion (m^3 of water)
0	37.8	322.0	886	1.1×10^{10}	1.8×10^{4}
3	37.8	1.7	0.9	1.1×10^{10}	1.8×10^{4}
6	37.8	1.5	0.8	1.1×10^{10}	1.8×10^{4}
9	37.8	1.3	0.7	1.1×10^{10}	1.7×10^{4}
12	37.8	1.1	0.7	1.1×10^{10}	1.7×10^{4}

* started with 38.0 g

In all simulations to calculate the dose rates are disregarded any shield, except that provided by air at normal conditions for temperature and pressure. Two radiation source terms have been determined: the first using the term source generated by ORIGEN code and a second, much more conservative, in which all the activity calculated for the IF was considered due to the nuclide cesium-137 that has a unique gamma of 662 keV in its sequence of disintegration. The dose rate due to neutrons is negligible in relation to the gamma rays contribution. The simulations show that the activity after 12 months decay has a very strong contribution due to the ^{137}Cs and ^{147}Pm fission products.

Table 2 shows the calculated results of dose rates at discharge and after 6 months and 1 year of decay. In each situation the doses were calculated at three different points: on the surface (contact with the cladding) in the IF average height, on the surface and shifted 10 cm away from the IF average height, and at one meter distance. As it was to be expected the dose rates calculated considering the total activity due to the cesium-137 has more conservative values.

Table 2. Calculated neutron dose rates for instrumented fuel element using the MCNP code (Dalle, 2009).

		Radioactivity dose rate (mRem/h)		
Source term	Decay Time (months)	At contact in the IF average height	At contact and 10 cm distant of IF average height	At 1 m distant of the IF average height
ORIGEN	0	4.4E+05	4.1E+05	5.2E+03
ORIGEN	6	6.8E+03	6.3E+03	8.0E+01
ORIGEN	12	1.3E+03	1.2E+03	1.5E+01
Cesium 137	0	7.9E+06	7.3E+06	9.4E+04
Cesium 137	6	3.7E+04	3.4E+04	4.4E+02
Cesium 137	12	2.7E+04	2.5E+04	3.2E+02

4. DESCRIPTION OF THE RECOVERY WORKS

With the instrumented fuel element located in the well for storage of irradiated fuel elements (Fig. 5), it was lifted with the aid of the manipulation steel handle, in way that only the terminal part of the thermocouples was outside the water. Some lead bricks had been placed for improvement of the radiological shield as it can be seen in the Figure 6, but in some places the only shield was the water of the well. The radiation level was measured with a Geiger Counter. At the points where it had not the lead shield the radiation level was 22 mR/h. At the places shielded with lead the radiation level was little above the reactor room background radiation. The radiation level measured was smaller than the calculated results shown in Table 2 by the cesium-137 method, but of the same order of magnitude by the ORIGEN method.

Figure 5. Well for storage of irradiated fuel elements

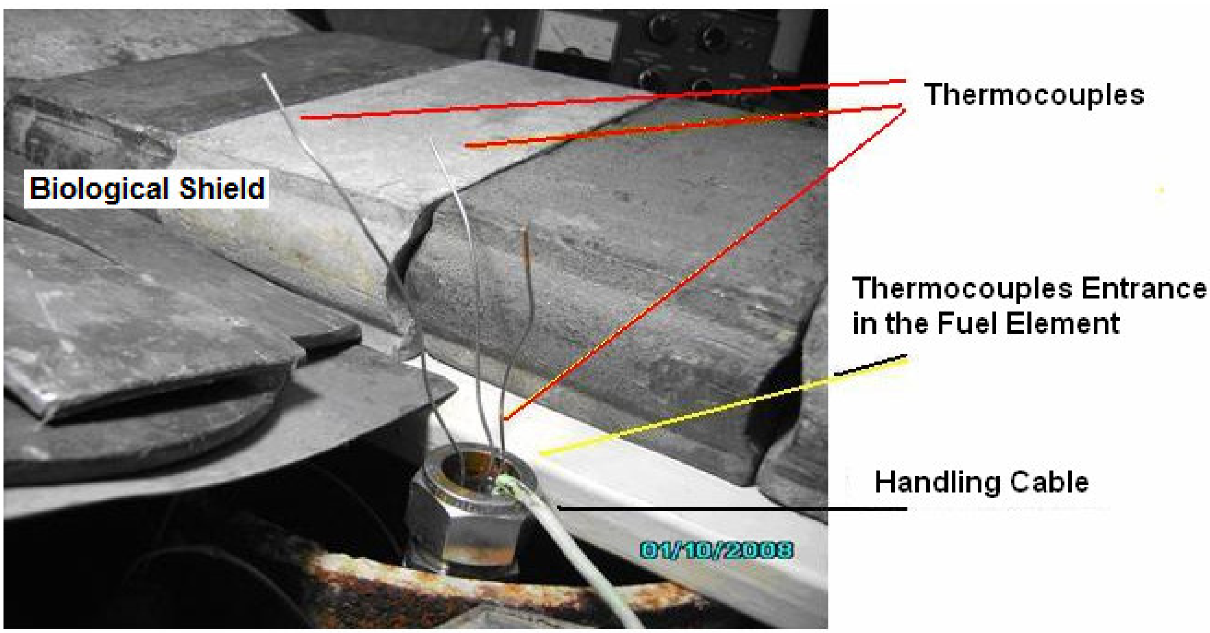

Figure 6. Place of the rupture of the thermocouples in the instrumented fuel element

3.1. Removal of the thermocouples stainless-steel shield

The methodology used for removal of the thermocouples shield was by an electrical pulse adjusted to burn only the stainless steel covering the thermocouples (Mesquita and Ladeira, 1985). Electrolytic capacitors had been loaded and its load was used to burn the shield. To find the correct value of electric charge, some preliminary tests with thermocouples of the same diameter of the IF thermocouples were performed (1.0 mm). It was confectioned two copper electrodes with a groove of 1 mm in order to accommodate the thermocouple before the electric pulse.

After the removal of the steel shield, the magnesium oxide (MgO) can be easily removed with aid of a clamp. In this way the two thermocouples element wire had been accessible. Figure 7 shows the assembly used to remove the thermocouples shield.

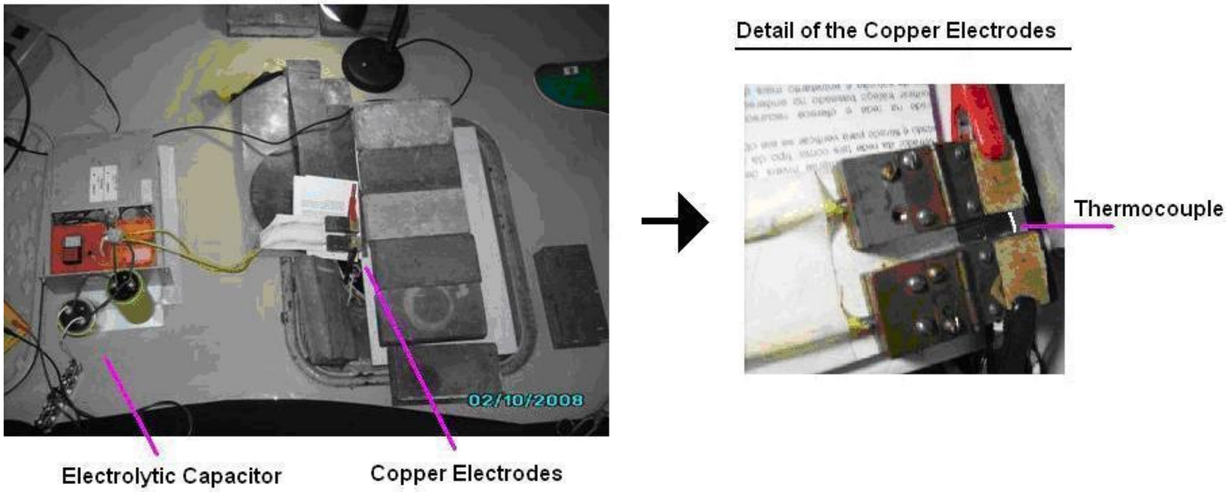

Figure 7. Assembly used for removal of the thermocouples shield by electric charge

3.2. Identification of the thermocouples wires

The type K thermocouples are composites of two conductors: a chromel alloy and an alumel alloy. The chromel is electrically positive and is non-magnetic, already the alumel is electrically negative and is magnetic. The identification was carried out through a small magnetic piece close to the wires, the one that is attracted will be the magnetic wire and the polarity is negative and it is the alumel alloy. The wires had been kept isolated between themselves and between them and the shield. Figure 8 shows two thermocouples after that the metallic shield and the magnesium oxide had been removed.

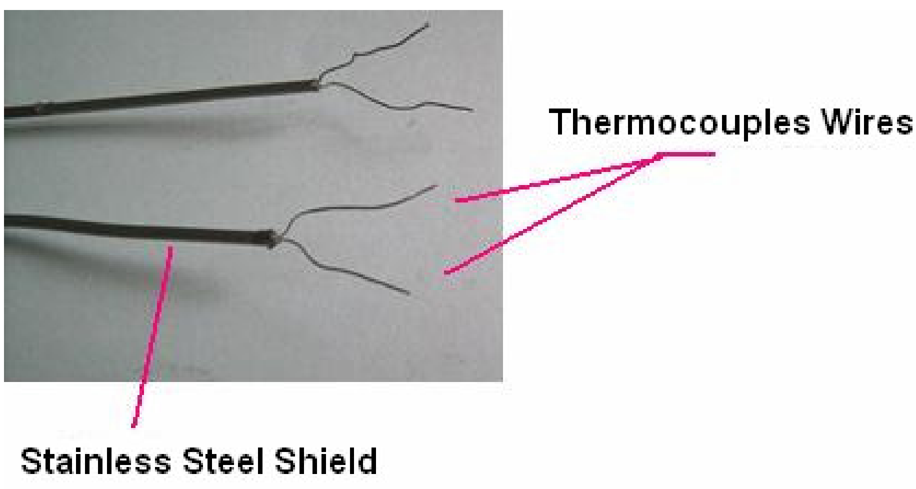

Figure 8. Two thermocouples after the shield and the MgO isolation had been removed

3.3. Connection of the thermocouples wires

After the thermocouples wires identification, they were fixed to the screws of the polarized female half connector (confectioned with chromel or alumel alloy). Epoxy resin (Araldite™ of normal drying) was placed to help to fix the thermocouples wires to the connector. The other halves of the connectors (male) had been connected at to new extension type K cable. Figure 9 shows the three thermocouples already fixed at female half of the connectors, this figure also show details of the thermocouple connection.

Figure 9. Thermocouples wires fixed on the connectors

3.4. Quality Control

The isolation between thermocouples wires and the stainless shield and the continuity of the wires were tested using a digital multimeter. The temperature was measured with the extension cable connected to one digital temperature indicator. Table 3 shows the results.

Table 3. Thermocouples measurements

Thermocouple Position	Wire Electrical Resistance [Ω]	Isolation [Ω]	Temperature [^{o}C]
Superior	85.0	22	23.4
Medium	87.4	20	23.6
Inferior	86.1	30	24.2

The thermocouples isolation was very lower than new one and the wire electrical resistances (loop continuities) are correct to these thermocouples kind and dimensions. The water temperature was of the same magnitude order of a calibrated thermocouple that was inserted in the well. Thus, it was concluded that the instrumented fuel element could return to the reactor core to monitor the temperature.

It was made the connection of the connector female half (linked to the thermocouples wires) to the male part of the connector (linked to the extension cables). Layers of silicon rubber were placed inside and around the connector to mechanical and electrical protection. On the next day the IF was lowered until the bottom of the irradiated fuels storage well immersed in water (3m deep). The thermocouples extension cables were connected to the TRIGA IPR-R1 data acquisition system (Mesquita e Rezende, 2004). It was observed that two of the three thermocouples did not indicate correctly the temperature anymore.

4. CONCLUSION

At the moment only one of the IF thermocouples is working and measuring the water temperature of the irradiated fuel storage well, the values are close to the surrounding temperature. The behavior of this thermocouple is unsure if the IF is used to monitor the reactor core operational temperatures, that is around 190^{o}C, at 100 kW (or 300^{o}C at 250 kW). It is recommended to place the IF in a dry local, with appropriate radiological shield, and keep the work to recover the thermocouples. The heatload of the irradiated fuel will provide the heat to dry the magnesium oxide (MgO) used in the isolation between the thermocouples wires and between them and the stainless steel cladding. External source of heat like electrical resistor can also be used to dry the thermocouples elements isolation (MgO).

It is emphasized here the importance of the presence of at least two instrumented fuel elements in the reactor core as current specification of General Atomics Electronic Systems Inc (2008) and as usual in several TRIGA reactors around the world. The IAEA (1995) recommends to monitor the core temperature in all operations of research nuclear reactors. The fuel temperature is the main operational nuclear reactor parameter and it must provide a signal that can be utilized in an automatic mode to prevent the value of the temperature of exceeding the safety limit. The fuel temperature was adopted in the IPR-R1 TRIGA Safety Analysis Report (CDTN/CNEN, 2007) as a safety operational limit. The fuel temperature should not exceed 550 °C. In some operations of the IPR-R1 reactor at 250 kW the fuel center temperature in the hottest core position reaches 310 °C (Mesquita, 2005).

The instrumented fuel element is the main tool used for operational parameters investigation in the thermal hydraulics experiments performed in TRIGA IPR-R1. In addition to recover the actual instrumented fuel element it is recommended to purchase a new one, whose current price is about 80,000 €, as proposed by the manufacturer TRIGA International (2008).

3. ACKNOWLEDGEMENTS

The authors express their thanks to the *Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG)* for the financial support.

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