

STATUS OF THE DEVELOPMENT OF A FUEL ASSEMBLY DECAY HEAT CALORIMETER FOR THE IEA-R1 NUCLEAR RESEARCH REACTOR

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ABSTRACT

The heat release due to decay of fission products following a nuclear reactor shutdown is important matter for determining cooling requirements as well as for predicting postulated accident consequences. Accurate evaluation of decay heat can also potentially provide independent data for the cross examination of fuel burnup calculations, which is useful where few resources are available for examination of spent fuel. The evaluation of decay heat from unloaded fuel assemblies of the IEA-R1 research reactor was proposed in order to seize that opportunity. With that purpose a special measuring device is under development at the Nuclear and Energy Research Institute (IPEN). Since average heat flux as low as $0.1\text{W}/\text{cm}^2$ is expected and since decay heat release must be accurately evaluated, the device design had to overcome the difficulties of measuring small amounts of heat released over a large boundary surface. The design had also to ensure the safe cooling of the fuel assemblies and proper radiological protection for the personnel. In view of the tight constraints, a novel design was adopted. The device features a submersible measurement chamber, which allows all measurement procedures to be performed without removing the fuel assemblies from the reactor pool, and an array of semiconductor thermoelectric modules, which provides highly accurate decay power measurements. The assemblage of the device is currently in progress, the main parts have already been acquired or manufactured and key components passed partial tests. Commissioning and main experiments will be performed up to the end of 2019.

1. INTRODUCTION

Accurate and reliable determination of actual fuel burnup is worth pursuing because it affects neutronic and physical properties of structural materials of the fuel assembly and of the fuel itself, but also because it creates an opportunity to corroborate and/or to improve burnup prediction methods. In order to fulfill this purpose, some fission products have properties that make them particularly useful: ^{148}Nd , ^{137}Cs and ^{144}Ce are often used as fuel burnup monitors [1].

The IEA-R1 is the 5MW pool type light water research reactor operated by the Nuclear and Energy Research Institute (IPEN) at São Paulo, Brazil. The facility supports researches in a wide range of fields, since 1957 [2]. Nevertheless, as far as the assessment of fuel assembly actual burnup is concerned, few resources are presently available, and most of the current researches rely on the burnup predictions only.

Because spent fuel examination capability lacks, any independent means that could help in assessing actual fuel burnup is worthy. Yet, as decay heat is correlated to the inventory of fission products, it is also correlated to the actual fuel burnup. Hence, the experimental decay heat evaluation is thought a potential, accessible means to corroborate burnup predictions. It was in that context that an opportunity was found to develop a calorimeter applicable to the fuel assemblies unloaded from the IEA-R1 research reactor. Before presenting the general aspects of that project a few remarks must be made regarding the heat generation from light water reactors in shutdown condition.

2. REMARKS ON HEAT GENERATION AFTER REACTOR SHUTDOWN

The reaction of nuclear fission of the ^{235}U isotope can be expressed as [3]:



In Eq. 1, the fission reaction products are neutrons, gammas, betas, neutrinos and the daughter lighter nuclei. The daughter nuclei tend to be neutron-rich, which makes them unstable and prone to subsequent nuclear decay [3]. In addition, some neutrons released by fission reactions will be captured in the fuel, forming unstable, activated nuclei [4]. Provided its surroundings have proper geometry and isotopic composition, the neutrons released by fission will play a role in establishing a chain reaction, with a net release of energy in the order of 200MeV per fission [3].

When a typical ^{235}U -fueled, water-moderated nuclear reactor is led to a shutdown condition, effectively breaking the chain of fission reactions, some heat generation persists inside its fuel, due to fissions induced by delayed neutrons and to decaying of unstable fission and activation products. The rate of heat generation after reactor shutdown is a relevant matter when assessing cooling requirements in normal reactor conditions and/or accident consequences following abnormal events. The rate of heat generation by delayed neutron fissions falls exponentially with the time elapsed since shutdown, having a period in the order of tens of seconds [4], which makes it hardly relevant after the first hour following the reactor shutdown. As the delayed neutron fissions vanish, the major sources of shutdown heat generation are the β - and γ -decay of fission products. All the energy from the β -decay is deposited in the fuel. On the other hand, part of the γ emissions will escape the reactor core, depositing its energy in its surroundings. In addition, neutron capture by fertile materials and fission products generates activation products, which eventually decay, delivering a minor contribution to the total decay heat. Long-term, accurate predictions must not neglect the effect of neutron capture.

As a first approximation the rate of energy release due to beta and gamma emissions from decaying fission products may be expressed by the empirical equations [4]

$$\beta \text{ energy release rate} = 1.40t'^{-1,2} \frac{\text{MeV}}{\text{fission} \cdot \text{s}} \quad (2)$$

$$\gamma \text{ energy release rate} = 1.26t'^{-1.2} \frac{\text{MeV}}{\text{fission} \cdot \text{s}}, \quad (3)$$

where t' is the time since the occurrence of fission, in seconds. The decay heat power can be predicted by integrating (2) and (3) over the reactor operation time [4]:

$$\frac{P}{P_0} = 0.066 \left[t_s^{-0.2} - (t_s + \tau_s)^{-0.2} \right] \quad (4)$$

where t_s = time since reactor shutdown, P = decay power, P_0 = constant operating power level prior to shutdown, τ_s = period the reactor operated at power P_0 . Equations 2 to 4 are accurate within a factor of 2 in the range $10 \text{ s} < t' < 100 \text{ days}$.

Decay heat may also be predicted in a thorough way, by taking the system of first order linear differential equations that describe formation and decay of fission products [5]:

$$\frac{dN_i}{dt} = -(\lambda_i + \sigma_i \phi) N_i + \sum_j f_{j \rightarrow i} \lambda_j N_j + \sum_k \mu_{k \rightarrow i} \sigma_k \phi N_k + y_i F \quad (5)$$

where the subscripts i, j, k refer to each kind of nuclide that may be found in the reactor core, N = number of nuclides present in the reactor core, λ = decay constant, σ = average cross section, ϕ = neutron flux, $f_{j \rightarrow i}$ = probability of a j -type nuclide to decay into a i -type one, $\mu_{k \rightarrow i}$ = number of i -type nuclides produced per neutron capture in k -type nuclides, y = fission yield, and F = the fission reaction rate. Once the isotopic inventory is found by solving Eq. 5, the decay heat may be predicted by using the following [5]:

$$P(t) = \sum_i (E_{\alpha,i} + E_{\beta,i} + E_{\gamma,i}) \lambda_i N_i(t) \quad (6)$$

where t is the time since shutdown, the subscripts α, β and γ refer to α -, β - and γ -decay, P =decay power, E_i = average energy released in decay of i -type nuclides.

In order to allow the accurate prediction of decay heat from nuclear fuel while avoiding complex summation calculations, the standard procedure ANS-5.1 was firstly proposed by the American Nuclear Society in 1971 [6]. Revisions of the ANS-5.1 have since been released with improvements that reduce the inaccuracies of the predictions it delivers. The most recent release (ANSI/ANS-5.1-2014, R2019) is able to predict decay heat contributions from ^{239}U , ^{239}Np and other actinides, and applies to decay times of up to 10^{10} s after shutdown [7].

3. THE IEA-R1 FUEL ASSEMBLY CALORIMETER PROJECT

The IEA-R1 Fuel Assembly Calorimeter (IFAC) was devised in order make possible the experimental evaluation of the decay heat released from standard IEA-R1 unloaded fuel assemblies. To fulfill its purpose it must be able to accurately measure decay heat power as high as 1000W. Above all, the use of the device must be arguably safe, particularly regarding

the cooling of the fuel assembly subject to experiments and preservation of radiation shielding for the personnel.

Research in literature shows a few examples of calorimetric experiments performed on fuel assemblies. In-site calorimetric measurements on BWR-type fuel assemblies were reported in 1982 by GE-Morris Operation. That calorimeter was composed by two concentric pipes with an insulated annular space. Experimental data were collected from resistance temperature detectors [8]. Another thermal power measuring device was developed in order to measure decay heat of fuel assemblies unloaded from the Japan Power Demonstration Reactor (JPDR) and the Japan Materials Test Reactor (JMTR). That device consisted of a water circulating loop, with a calibration heater and a measurement chamber to house the fuel assembly under test. Measurements performed on fuel assemblies within weeks to months since reactor shutdown were reported in 1988 [9]. A more sophisticated calorimeter was recently developed at the Swedish Central Interim Storage Facility for Spent Fuel, in collaboration with the Oak Ridge National Laboratory (USA), as part of a project aimed at providing experimental data for the validation of decay heat prediction methods and expanding regulatory texts on decay heat. That equipment applies to PWR- and BWR-type fuel assemblies and relies on arrays of temperature sensors and γ -ray detectors to produce decay heat data. Measurements in the range 50W-900W, with uncertainties in the range 1W-6W were reported in 2008 [10, 11].

Early in the project the choice of a calorimeter design for the IEA-R1 fuel assemblies was found tightly constrained: the target measuring range was considerably wide; the geometry of the measurement chamber had to suit the relatively large fuel assembly dimensions; materials employed must withstand the radiation exposure; the fuel assemblies must be kept underwater to ensure cooling and shielding, which implies that the main instruments must have water-proof electric connections. In view of those constraints, a choice was made to develop the IEA-R1 Fuel Assembly Calorimeter (IFAC) from scratch.

The design eventually converged to what can be described as a variation of a conduction calorimeter. Its main part consists essentially in a submersible vessel, capable of hosting a standard IEA-R1 fuel assembly (Fig. 1).

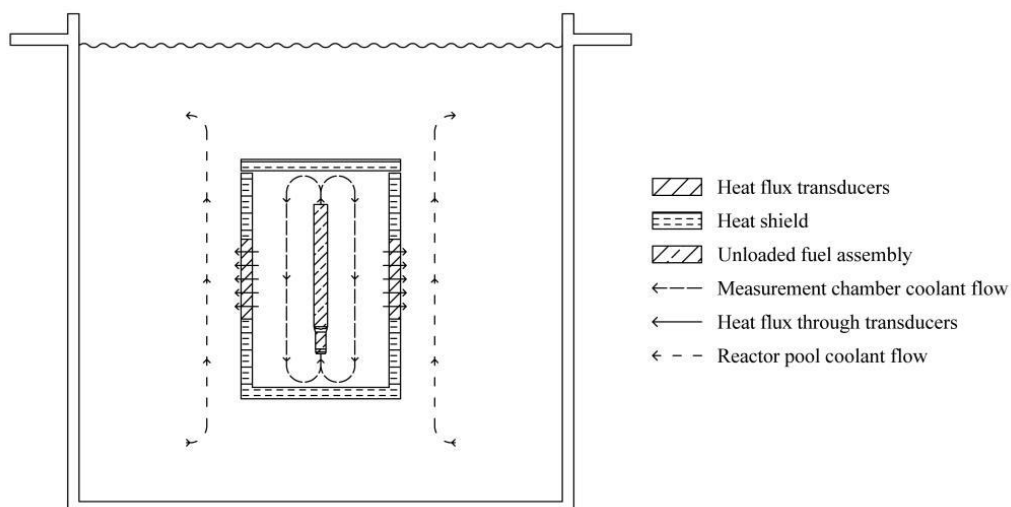


Figure 1: Cooling of a fuel assembly in the reactor pool, while decay heat is evaluated.

While measurements are performed, natural convection of the coolant inside the measurement chamber removes heat from the fuel assembly. The heated coolant eventually reaches the internal side walls of the chamber. Between the double walls of the vessel, heat conducting transducers provide a path for the decay heat to reach the external surface of the vessel. Finally, as the coolant flows outside the calorimeter, the reactor pool absorbs the decay heat.

Thermoelectric modules (TEM) are used in the IFAC to perform the function of heat flux-to-voltage transducers (Fig. 2). Each TEM is itself an array of Te-Bi, n- and p-doped, semiconductor thermoelectric pairs. Internally, its semiconductor blocks are all connected in a single series electric circuit. Also, all semiconductor blocks are in thermal contact with both the cold and the hot faces of the TEM.

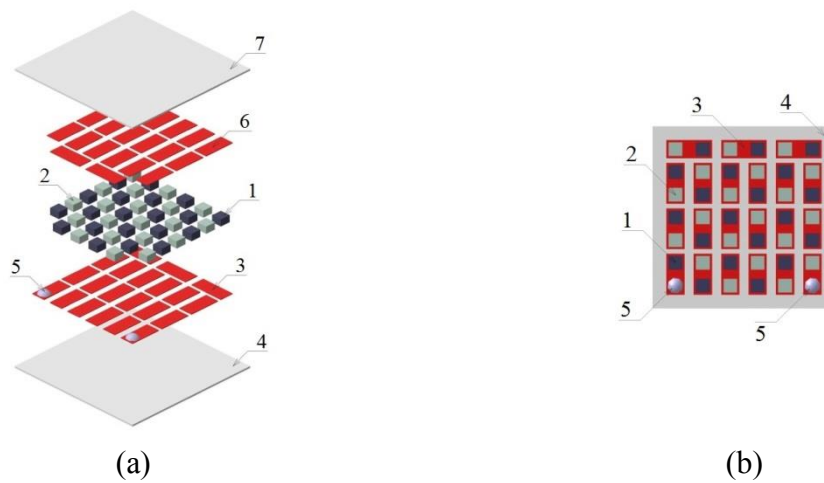


Figure 2: Typical thermoelectric module: exploded view (a), with n- and p-type semiconductor blocks (1, 2), conductive metal pads (3, 6), cold- and hot-face ceramic substrates (4, 7) and solder pads for the electric connections (5); cut along the plane of semiconductor blocks (b).

Due to the Seebeck effect, as a temperature difference develops between the hot and cold faces of the TEM, a voltage develops at the extremes of the electric circuit:

$$V_S = \alpha \Delta T, \quad (7)$$

where V_S = aggregate Seebeck voltage, α = aggregate Seebeck coefficient, ΔT = temperature difference between the hot and cold faces of the TEM [12]. Yet, since IFAC data acquisition inputs require very small charging/discharging electric currents, the power generated inside each TEM due to Joule effect can be neglected, which makes the heat reaching the hot side of the TEM essentially the same as the heat leaving the cold side, so that

$$\Delta T = \dot{q} R_{th}, \quad (8)$$

where \dot{q} = conductive heat transfer rate and R_{th} = thermal resistance for the conductive heat transfer that occur between the hot and cold faces of the TEM. Eqs. 7 and 8 can be combined to provide a correlation between the power conducted through the TEM and the Seebeck voltage it develops:

$$\dot{q} = \frac{1}{\alpha R_{th}} V_s. \quad (9)$$

As long as all the relevant temperatures remain in a range where α and R_{th} can be assumed constant, Eq. 9 can be extended to the n -sized TEM array:

$$\sum_{i=1}^n \dot{q}_i = \frac{1}{\alpha R_{th}} \sum_{i=1}^n V_{s,i}. \quad (10)$$

Now the decay power may be assumed constant during each finite calorimetric measurement, provided the time since reactor shutdown is long enough. Indeed, in order not to exceed the heat removal capability of the IFAC, no experiment will be allowed in the first 10 hours after shutdown. In this case, conservation of energy applied to the measurement chamber volume boundary gives:

$$P_d = \sum_{i=1}^n \dot{q}_i + \dot{q}_u = \frac{1}{\alpha R_{th}} \sum_{i=1}^n V_{s,i} + \dot{q}_u, \quad (11)$$

where P_d = power deposited inside the measurement chamber and \dot{q}_u = total unaccounted heat leaving the chamber. Eq. 11 shows that a simple, linear correlation exists between the cumulative Seebeck voltage and the total power deposited in the measurement chamber. Because the best achievable correlation is to be found experimentally and since both α and R_{th} will be subject to radiation induced drift, the measurement chamber has a well-known heat source embedded to allow easy, periodic calibration.

In order to minimize the heat transfer that could not be accounted and would add to the uncertainty of the results, the TEM array is placed along the path of least thermal resistance between the fuel assembly and the main volume of coolant, in the reactor pool. While measurements are performed, as heat power is conducted through the transducers, a Seebeck voltage is generated according to Eq. 11. The resulting analog signal is wired out of the coolant pool and until the control cabinet, on the pool side, where the data acquisition system performs digital conversion and proper data recording.

A submersible unit allows all the measurement procedures to be conducted without removing the fuel assemblies from the reactor pool, thus ensuring the proper removal of decay heat and preserving shielding for the personnel. Its measurement chamber suits any standard IEA-R1 fuel assembly. Except for the segment with an array of heat flux transducers, the chamber is thermally isolated from the main volume of coolant, in the reactor pool. Its side walls are hollow, and its annulus is evacuated in order to minimize convective heat losses, that would add to measurement inaccuracy (Fig. 3).

The submersible unit has a movable top cap, designed to allow a minimal coolant circulation from and to the measurement chamber, which keeps hydrostatic inside-outside pressures even, while avoiding higher heat loss. The cap has a small centrifugal water pump embedded, which will be able to reduce temperature gradients inside the measurement chamber by enforcing the otherwise natural convective flow of coolant. An embedded video camera will provide images to help operators in correctly placing the fuel assembly to be tested. The cap has also an air pocket where a wire resistor is placed. That resistor will be powered to rise the local temperature to the point that minimizes the unaccounted heat transfer from the measurement chamber through the cap. The bottom end of the unit also features an air pocket with a controlled heater, to minimize unaccounted heat transfer through that end.

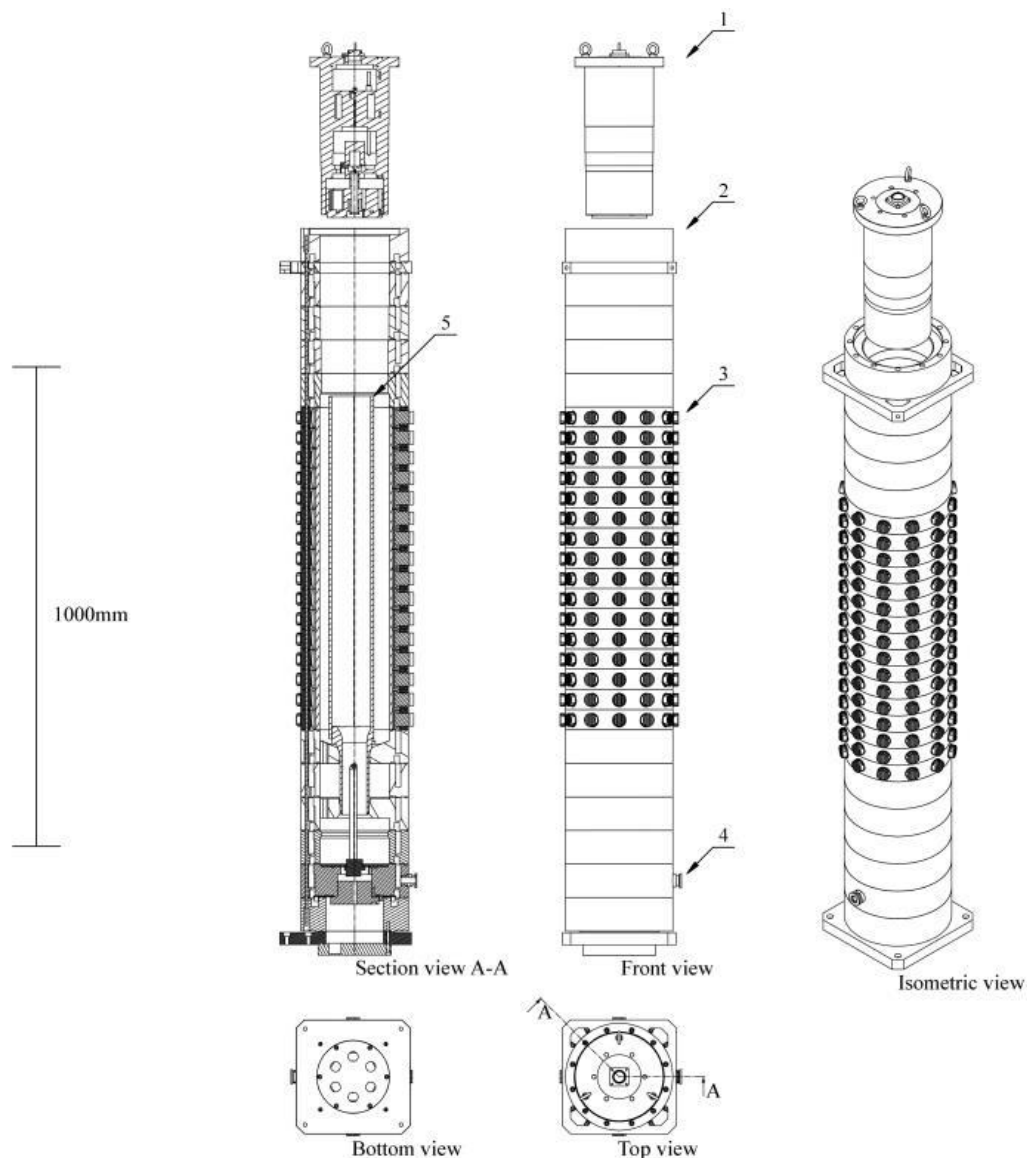


Figure 3: Drawings of the IFAC, with top cap (1), double-walled vessel (2), TEM heat sinks (3), the evacuation port (4) and a fuel assembly shown for reference (5).

The hot face of each TEM is kept in thermal contact with the internal wall of the measurement chamber, while the cold face is kept in thermal contact with an aluminum heat

sink. Holes in the external wall of the vessel allow the heat sinks to reject heat directly to the pool coolant. As the annulus is evacuated, the pressure outside the vessel compresses each heat sink against the respective TEM, in a way that improves the thermal contacts and yet allows for the accommodation of thermal expansions. The IFAC houses a total of 192 heat flux transducers, which provide heat removal capability in the full range of operation while keeping the temperature of the coolant below 60°C.

Once placed inside the measurement chamber, the fuel assembly to be tested is supported from its bottom nozzle, in a way that keeps the coolant free to circulate through the channels between the fuel plates. The heat removal capability of the measurement chamber relies on passive components/mechanisms only. Though the measuring range extends up to 1000W, the measuring chamber will safely remove power as high as 2000W. An embedded electric heater with a closed-loop power control will be available to allow recalibration of the heat flux sensors whenever required. The electric heater will deliver up to 1000W power.

The IFAC has a movable control cabinet that hosts an alarm panel, as well as a control panel for the test and calibration heater, and the associated circuitry. The control cabinet also hosts the data acquisition system, supported by a PC-type computer, and all the signal conditioning circuits. An alarm will sound should abnormal temperature be found in the measurement chamber. The alarm panel houses two redundant controllers, which rely on sensors placed in the top cap and inside the chamber.

4. PROJECT STATUS

The IFAC was granted funding in 2017. So far the project has delivered the submersible unit and the control cabinet.

3.1. Submersible Unit

The double-walled vessel was built as a set of segments, mainly in order to ease mechanical machining (Fig. 4). The section that faces the heat flux transducers was built in aluminum, due to its high thermal conductivity and because it is suited for use in the reactor pool. On the other hand, all the parts of the vessel that work as heat transfer barriers were built in High Density Polyethylene (HDPE), due to its very low thermal conductivity. The top cap was also mostly built in HPDE.

An external metal frame was added to provide stable skids and further structural support to the unit, both during transportation of the device and while in the reactor pool.

3.2. Control and Instruments Cabinet

A single control cabinet contains all the features the IFAC need to perform both the heat decay measurements, periodic tests and calibrations. The control cabinet contains an uninterruptible power supply unit for the essential subsystems, which enables the operators to interrupt the activities in a timely, safe manner, should a power outage affect the reactor building. The cabinet hosts the electric heater power drivers, which provide a stable, closed-loop regulated power supply during calibration and test procedures. In order to minimize electromagnetic interference noise, the driver relies on solid state relay switching. The

cabinet also hosts the power driver for the centrifugal water pump and for the top and bottom air pocket heaters (Fig. 5).



Figure 4: The submersible unit of the IFAC.



Figure 5: The control cabinet of the IFAC.

The cabinet hosts a data acquisition system that provides 16 input channels at 16-bit resolution, for the TEM readings, as well as 16 auxiliary input channels at 12-bit resolution, for pressure and temperature measurements. The cabinet has also a clock synthesizer circuit module, which enables the data acquisition system to perform power grid synchronized

sampling. The cabinet also hosts the AC-to-DC power adapters, a signal conditioning circuit module for a vacuum meter, a current sensing module that plays a role in the power control of the calibration heater, overload protection fuses and circuit breakers.

Since it could otherwise lead to exceeding the calorimeter rated power, potentially compromising the proper cooling of the fuel assembly, the calibration heater must be kept off whenever a fuel assembly is inside the measurement chamber. In order to comply with reliability requirements, switching between measurement and calibration modes is performed manually, the heater is disabled when in measuring mode, and enabled when in calibration mode, and the logic circuit is implemented with electromechanical devices. That exception aside, most of the control/measurement functions were implemented on the National Instruments LabVIEW platform.

The main cabinet functions have been tested in simulated anticipated conditions, performing accordingly.

3.3. Next Developments

A virtual control panel will provide a flexible yet safe means for both the control of the IFAC and the handling of acquired data. The virtual control panel relies on the LabVIEW platform and is currently in process of implementation.

When fully operational, the IFAC will be transferred to the IEA-R1 reactor building (Fig. 6). Main experiments will be performed with unloaded standard fuel assemblies. Preliminary results are expected by the end of 2019.

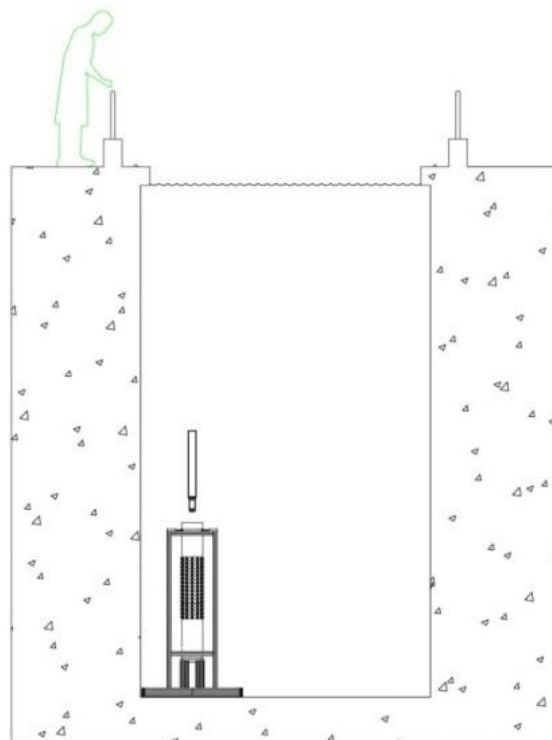


Figure 6: Illustrative cut view of the IEA-R1 building, with personnel on the pool side, the IFAC and a fuel assembly underwater.

4. CONCLUSIONS

The IEA-R1 Fuel Assembly Calorimeter was proposed in a scenario where little information is available to corroborate fuel burnup predictions. The IFAC was devised in order to make possible the measurement of decay heat from fuel assemblies unloaded from de IEA-R1. It is expected to deliver decay power measurements ranging up to 1000W. The design of the IFAC was found too constrained to rely on off-the-shelf solutions, so it was developed from scratch. The IFAC consists mainly in a submersible unit and a control cabinet.

In order to ensure proper cooling of the fuel assembly under test and radiation shielding for personnel, all the measurement procedures are performed with no need to remove the fuel assemblies from the reactor pool. Heat removal from the fuel assembly under test relies on passive components and mechanisms only, which helped in limiting the number of conceivable failure modes. The submersible unit consists essentially in a double-walled with a removable cap. Power measurement relies on an array of embedded semiconductor thermoelectric devices. Raw data will be wired out of the coolant pool until the pool side control cabinet, where digital conversion and proper recording will be performed.

As per the preparation of this work, the project had produced the control cabinet with all the hardware capabilities to perform both measurements and control of the IFAC already implemented. All the parts of the submersible unit had been manufactured, with its assembly currently in progress and its performance test at wet conditions due to follow soon. The virtual control panel is currently under development, as well as the pool side experimental setup. Main experiments will be performed with standard fuel assemblies, and are due to be started by the end of 2019.

Once fully operational, the IFAC will be able to provide data on the unloaded fuel assemblies which can potentially be used for burnup prediction cross-examination. By providing independent verification of total decay heat, in the future the use the calorimeter may also contribute to the safety of transportation and storage of spent fuel assemblies.

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REFERENCES

1. J. G. Tyror, "Reactor Burnup Physics," *IAEA Panel Proceedings Series*, Vienna, 12-16 July 1971, pp.47-93 (1973).
2. C. B. Zamboni, *Fundamentos da Física de Nêutrons*, Livraria da Física, São Paulo Brazil (2007).
3. J. J. Duderstadt, L. J. Hamilton, *Nuclear Reactor Analysis*, John Wiley & Sons, New York USA (1976).
4. N. E. Todreas, M. S. Kazimi, *Nuclear Systems: Thermal Hydraulic Fundamentals, vol. I*, Hemisphere, New York USA (1990).

5. "Decay Heat and Nuclear Data," <https://www.intechopen.com/books/nuclear-reactors/decay-heat-and-nuclear-data> (2012).
6. American National Standards Institute, *Decay Heat Power in Light Water Reactors*, ANSI, La Grange Park USA (2005).
7. "Decay Heat Power in Light Water Reactors: Standard by American Nuclear Society," https://www.techstreet.com/ans/standards/ans-5-1-2014-r2019?product_id=1894076 (2014).
8. J. W. Roddy, J. C Mailen, *Radiological characteristics of light-water reactor spent fuel: a literature survey of experimental data*, Oak Ridge National Laboratory, (1987).
9. K. Murakami, I. Kobayashi, *Measurement of Decay Heat from Spent Fuel Assemblies of JPDR and JMTR*, Japan Atomic Energy Research Institute, (1988).
10. B. D. Murphy, I. C. Gauld, *Spent fuel decay heat measurements performed at the Swedish Central Interim Storage Facility*, USNRC, (2010).
11. G. Ilas, I. C. Gauld, "SCALE analysis of CLAB decay heat measurements for LWR spent fuel assemblies," *Annals of Nuclear Energy*, **Volume 35**, pp.37-48 (2008).
12. G. S. Nolas, J. Sharp and H. J. Goldsmid, *Thermoelectrics: Basic Principles and New Materials Developments*, Springer Berlin Heidelberg (2013).