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SUMMARY AND KEY MESSAGES

The key goal of the European FP6 project MTR+I3 is to build durable cooperation between Material Testing Reactor (MTR) operators and relevant laboratories that can maintain European leadership with up-dated capabilities and competences regarding reactor performances and irradiation technology.
The MTR+I3 consortium is composed of 18 partners with a high level of expertise in irradiation-related services for all types of nuclear plants.
This project covers activities that foster integration of the MTR community involved in designing, fabricating and operating irradiation devices through information exchange, know-how cross-fertilization, exchanges of interdisciplinary personnel, structuring of key-technology suppliers and professional training. The network produces best practice guidelines for selected irradiation activities.
This project allowed to launch or to improve technical studies in various domains dealing with irradiation test device technology, experimental loop designs, and instrumentation. Major results are illustrated in this paper. These concern in particular: on-line fuel power determination, neutron screen optimisation, simulation of transmutation process, power transient systems, water chemistry and stress corrosion cracking, fission gas measurement, irradiation behaviour of electronic modules, mechanical loading under irradiation, high temperature gas loop technology, heavy liquid metal loop development, safety test instrumentation.
One of the promising benefits of this project is that it will most certainly lead to further collaboration within the involved partners regarding the development and utilisation of irradiation devices. In addition, most courses developed in the different institutes within the framework of professional training will probably continue beyond the end of the project.

In order to fulfil this goal, a dedicated public web site has been opened at the following address: www.mtri3.eu. It includes a summary of the project, links towards all the partners, the project organisation, leaders contacts for each activity and a summary of results in the areas listed above.

1 INTRODUCTION

Assessing the behaviour and characteristics of material and fuel under irradiation conditions is a key field for supporting existing nuclear power reactors and future reactors. Results from this research contribute amongst others to demonstrate safety cases, form the basis for the extension of operational lifetimes and economic optimisation of operation for power plants. Developments of innovative materials and fuels are on the critical pathway for most of Gen-IV reactors.
Material Testing Reactors (MTRs) are needed to carry out such studies and have been key tools to reach the present nuclear industry maturity.
Several framework programs have been addressing MTRs domain: FEUNMARR a 5th FP thematic network (Future European Union Needs in MAterial Research Reactors, Nov. 2001 – Oct 2002) and JHR-CA, a 2004-2005 coordination action (Jules Horowitz Reactor Co-ordination Action). As a result of these first steps, it appears that

- Taking into account plant lifetime management, the development of the third generation all along the century, the key challenges raised by Gen-IV design, it is mandatory to sustain the MTR experimental activity at a high level of performance. Up to now, Europe has a clear leadership in this field and the goal is to keep this expertise.

- Taking into account the present ageing of European MTRs, at least one new MTR has to be built in Europe to meet the above needs (FEUNMARR conclusion). The JHR project, presently under construction in Cadarache, copes with this context and will be operated as a European and world-wide user-facility. At least two other MTRs are planned and presently under design in Europe: MYRRHA, a fast spectrum experimental facility based on an Accelerator Driven System (ADS) in Belgium, and PALLAS, a thermal reactor in the Netherlands primarily dedicated to radioisotopes production.

- Beyond the key issue of the infrastructure, it is of first importance to invest in know-how on experiments, to train new generations of scientific and technical staff in this field, to cross-fertilize the European expertise. This was not an easy objective in the past years due to a lack of investment in that field and due to the severe economical competition between European MTRs.

- The JHR-CA was a first attempt to overcome the above issues i) by creating a MTR community able to share views on experimental needs and technologies and ii) by defining the conceptual design for a set of up-to-date experimental devices for MTRs.

As a natural subsequent step, the MTR+I3 (Integrated Infrastructure Initiatives for Material Testing Reactor innovations) has been launched over the period 2006-2009 to reinforce European experimental capabilities for testing material and fuel under irradiation by encouraging a durable cooperation between labs involved in MTR activities and by promoting technological related innovations. This paper illustrates several fields that have been investigated within MTR+I3.
The MTR+I3 consortium is composed of 18 partners with a high level of expertise in irradiation-related services for all types of existing and future European Nuclear Plants:

MTR+I3 partnership		
Commissariat à l’Energie Atomique	CEA	France
Atominstitut der Oesterreichischen Universitaeten	ATI	Austria
BEL V (subsidiary of FANC)	BEL V	Belgium
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas	CIEMAT	Spain
Gesellschaft fuer Anlagen- und Reaktorsicherheit	GRS	Germany
Institut de Radioprotection et de Sûreté Nucléaire	IRSN	France
Instituto Tecnológico e Nuclear	ITN	Portugal
European Commission - Joint Research Centre - Institute for Transuranium Elements	EC-JRC ITU	Germany
Universitaet Karlsruhe (Technische Hochschule) Institute for Nuclear technology and Reactor Safety	Uni-Ka	Germany
Hungarian Academy of Sciences KFKI Atomic Energy Research Institute	AEKI	Hungary
National Centre for Scientific Research Demokritos	NCSR-D	Greece
Nuclear Research and consultancy Group	NRG	The Netherlands
Paul Scherrer Institute	PSI	Switzerland
Studie Centrum voor Kernenergie – Centre d’Etudes de l’énergie Nucléaire	SCK.CEN	Belgium
Studsvik Nuclear AB Fuels and material	Studsvik	Sweden
Regia Autonoma pentru Activitati Nucleare / Sucursala Cercetari Nucleare (SCN), Pitesti	SCN-NRI	Romania
Ustav jaderneho vyzkumu Rez, a.s. / Nuclear Research Institute Rez, plc.	UJV	Czech Republic
VTT Technical Research Centre of Finland / Materials Performance	VTT	Finland

2 INNOVATIVE TEST DEVICE TECHNOLOGIES

MTR+I3 covers networking activities that foster integration of the MTR community involved in designing, fabricating and operating irradiation devices through information exchange, know-how cross-fertilization, exchanges of interdisciplinary personnel, structuring of key-technology suppliers and professional training. The network produced best practice guidelines for selected irradiation activities.

Research activities focusing on the development and fabrication of innovative test devices that improve existing MTR experimental capabilities were envisaged that address safety issues, management of ageing and optimisation of current power plants, fast neutron reactors with associated fuel cycle (sustainability, actinide management), and technologies for high temperature reactors.

The scientific and technical challenges in the field of irradiation technology are manyfold and frequently with prototypical characteristics. Engineers working in this field need to integrate polytechnical sciences, s.a. mechanics, thermohydraulics, pneumatics, chemistry, nuclear sciences, electrical and electronical devices, sensors and instrumentation, automatic controls, safety engineering, computational skills as well as the application of codes and standards and quality assurance systems. Therefore the design, construction and operation of irradiation devices is a complex combination of multidisciplinary activities, often also within the framework of contractual and financial boundaries.

As examples, the following sections describe:

- Exchanges between MTR+I3 partners in the so-called “network activities” about test device manufacturing practices and measurement best practices.

- Technical developments in test device technologies about neutron screen for advanced fuel and transmutation testing; power transient systems; technologies for studies dealing with water chemistry and for fission gas measurement
- The possibility to test electronics equipment under irradiation in order to improve the reliability of such components.

The technical activities produced also knowledge on MTR loop designs and developed some components and instrumentation for these loops. In particular loops are developed for studying materials behaviour under controlled mechanical loads and corrosion; for optimisation and improvement of reactor fuel; for the development of future reactors with novel coolants (including Helium, Supercritical Water, Lead or Sodium) that produce reduced waste with better fuel utilization; and instrumentation for safety testing. Some of these developments are tested out-of pile. As examples, the technical results about the device designed for material testing under controlled mechanical load, the design of a He loop and the design of a PbBi loop and studies devoted to instrumentation for safety testing will be also described in the following sections.

2.1 Test device manufacturing

In the next decade a new landscape will emerge among the Materials Testing Reactors (MTR) in Europe with some reactors closing down and new ones starting operation. The tendency will be to more and more open access on powerful MTRs through bilateral agreements or cross-participation in the reactor investments. The same tendency will concern companies or institutes involved in the test device manufacturing.
Within this context, the objective of the MTR+I3 networking activity of « manufacturing rigs/irradiation devices » was to improve the communication and the knowledge between the institutes involved in this activity and to prepare harmonization of the working practices.
The first objective has been reached during the 3 years of the project which consists in making participating Institutes’ manufacturing capabilities and working practices better known to each others. A screening of the manufacturing capability has been made through a questionnaire developed in collaboration with participants. An inventory of the various manufacturing capabilities was done on the following aspects: entity organisation, design capabilities, Quality Assurance and Project Management capabilities, manufacturing and testing capabilities. Many institutes dealing with designing and/or manufacturing of irradiation devices (and related equipment s.a. glove boxes) have participated (NRG, UJV, CEA, IRSN, ITU, SCK.CEN and SCN-NRI); but other smaller institutes generally linked to research reactors have been also involved as they could provide experiment parts to the reactors. Links between people dealing with that activity have been formed that will ease relationships in several fields in the near future. Need for mutual help has been evoked with supply of rare components or long lead time items, exchange of good fitters during assembly phases, advice for specific supplies and information when call for tenders are issued.
The second objective of this activity was to get the working practices harmonized in the long term. A first step has been performed with a comparison of the Realisation Standards currently used by the Institutes through an exercise. This exercise involves a real component made in the various Institutes. This comparison is made versus the RCC-MX (French conception guide) standard, an up-to-date standard developed and used by CEA for research reactors. By the end of the MTR+I3 project every participating institute will share what is required in the RCC-MX standard by comparison with its own requirements. Because people will be provided with all the exercises they should also understand the others’ requirements.

This activity has shown that major manufacturing Institutes in Europe use various realisation standards but these standards are not that different. In that context it is possible in the next years to subcontract realisation of irradiation device to the present main manufacturers. This is a major result since collaboration and optimisation of that capability in Europe is important to maintain some level of excellence in that domain.

2.2 Measurement best practices

Within an active competition framework, European MTRs have developed domestic experimental capabilities, know-how and technologies. There are no shared standards for important measurements such as nuclear heating in non-fuel materials or thermal balance in fuel ramp testing.
This MTR+I3 networking activity focuses on comparing the approaches that are used for the above-mentioned technical subjects. Providing benchmarking and recommendations as a best practice guide for measurement methods will increase the quality of MTRs offer to the benefit of End-Users.
For illustration, the nuclear heating in non fuel materials is presented hereafter. Nuclear heating has two main fields of interest:

- For the experiment design since this heating will determine the temperature of the experiment components, and thereby the safety and operational conditions.
- For analysis of experiment results since the sample temperature will depend on the nuclear heating in the structural components.

A detailed review has been made of the various approaches that have been used to determine the gamma heating in various European reactors. These techniques are:

- Calorimeters (Figure 1) with various materials.
- Gamma-selective self-powered detectors. They are basically Self-Powered Neutron Detectors (SPND's) in which the emitter material is chosen to have minimal neutron sensitivity and maximized gamma sensitivity.
- Gamma thermometers, such as a stainless steel chamber filled with argon or helium gas, in which the temperature of the Inner Heating Body (IHB) is raised substantially by nuclear heating (gammas and neutrons). The temperature difference between the tip of the IHB and the surrounding material is proportional to the local nuclear heating rate.
- Monte Carlo neutron physics computations using codes such as TRIPOLI4 or MCNP; this is considered as a powerful tool to assess the nuclear heating in the complete structure of the experiment taking in account geometry and gamma self-shielding.

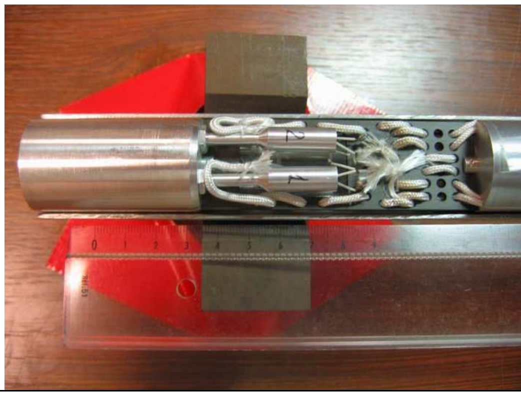


Figure 1 : The sensitive part of a differential calorimeter (CEA)

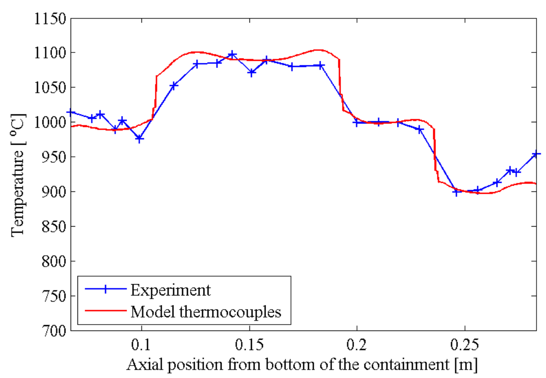


Figure 2: Comparison between predicted and measured temperatures in PYCASSO-I (axial profile)

- Experiment simulations coupling neutron physics and thermal computations are performed to be compared and rescaled to actual thermocouple measurements (see a High Flux Reactor example in Figure 2).

By combining results of the above mentioned techniques the European reactors are capable of making more and more accurate predictions of the nuclear heating and the temperatures inside the experiments.

2.3 Neutron screen development for transmutation and advanced fuel testing

Most of the Gen-IV reactors (SFR, LFR, GCFR and ADS) and fusion reactors have hard neutron spectra. There exist very few fast reactors and after the scheduled closure of the Phenix reactor in France, there exist no more operating fast reactors in Western Europe. The remaining fast reactors in the world are difficult to access and therefore irradiation testing in water-cooled MTR's is a logical alternative.

In some cases, for example to simulate Fast Reactor's (FR) it is required to harden the spectrum in irradiation experiments in MTRs. This can either be done by placing additional fissile material around the experiment or by placing a shield that absorbs thermal neutrons around the experiment. In some reactors (e.g BR2 or JHR) the experiment can be placed inside fuel assembly in which one or several of the inner plates have been removed. This enhances the fast neutron flux inside the experiment. Other examples in the past in BR2 reactor were the large sodium loops MOL 7C (for safety tests on SFR fuel bundles) and the large helium loops GSB (for testing of prototype GCFR fuel bundles), which were surrounded by a cadmium screen and irradiated inside special fuel elements in 200 mm channels. Hardening of the spectrum by increasing the amount of fissile material close to the experiment has also been envisaged within MTR+I3, but the additional cooling needed is found very complicated and costly. It has been concluded that in most cases an easier option to harden the spectrum is by removing thermal neutrons with a neutron absorption shield. Two important materials that can be used in neutron screening are cadmium and hafnium, which both have their advantages and disadvantages (Table 1):

Material	Melting temperature	Mechanical properties	Manufacturing characteristics	Thermal neutron absorption cross section	Isotopes relevant for neutron absorption	Thickness needed to reduce the thermal flux by 90%
Hafnium	++ (2233°C)	++	++	+/- (102 Barn)	All Hf isotopes	Approx. 4 mm
Cadmium	- - (321°C)	--	+/-	++ (2450 Barn)	^{113}Cd (12% abundance)	<500 micron

The extremely high neutron cross section of cadmium has the advantage that a very thin layer of cadmium is in principle sufficient to shield the thermal neutrons. The neutron screen should however be sufficiently thick in order to accommodate the burnup of the cadmium isotope ^{113}Cd with the high absorption cross sections. This ^{113}Cd isotope is only 12% abundant in natural cadmium. In hafnium all isotopes contribute to the neutron absorption (to a larger or smaller extent). This makes that for a somewhat longer irradiation time the cadmium screen should be sufficiency thick in order to prevent for instance a sudden power increase (and non typical irradiation conditions) in a cadmium shielded experiment. For hafnium such a drastic change of the neutronics conditions with time is absent. Combining the cadmium with hafnium into one shield gives an effective neutron shield. The hafnium should preferably be located at the outside of the cadmium. This makes that the hafnium absorbs most of the neutrons, thereby keeping the ^{113}Cd transmutation rate low and keeping the shielding effective for a long period.

The low melting temperature of cadmium (321°C) and the large thermal expansion at melting makes that the engineering of a cadmium screen is more complicated than that of a hafnium screen. Fabrication tests have been performed on hafnium screens in order to assess the options that exist to fabricate suitable shields. The approach used for the TIG welding of hafnium foils (Figure 3) is described. Visual inspection has been performed on the irradiated hafnium shield after irradiation and it is observed that after 150 days in the cooling water (7 m/s) the shield shows no visual modification.

No general conclusions could be reached on which is the optimum neutron screen design. The suitability depends strongly on the boundary conditions, such as spectrum needed, space available etc. The knowledge gained in MTR+I3 makes it feasible to design optimized neutron shields or Gen-IV and fusion experiments that are now under design in European reactors.

Figure 3 : Photo of a TIG welded hafnium tube, made from hafnium foil.

The impact of a shielded High Flux Reactor (HFR) experiment on the financial and safety aspects of the HFR, together with the technical impact on the other experiments has been discussed. As an example in this analysis the experience from an ongoing experiment in the HFR is used. This experiment has a neutron absorption shield (hafnium and cadmium) of 30 mm diameter and 400mm height. The screen is placed on one of the high flux locations of the HFR, with three experiments nearby. From the present analysis it is concluded that this screen has no significant safety consequences in case of the HFR. The main impact of a high neutron absorption experiment comes from the cycle length which will be reduced. This reduction of the cycle length can be avoided but with significant financial consequences (by either increasing the number of fresh fuel elements at the start of the irradiation or decreasing the amount of highly absorbing material such as radioisotopes for medical or industrial purposes). In addition, the neutron screen has a technical impact on the neighbouring experiments:

- the local neutron flux depression may cause that the flux conditions are no longer suitable for the neighbouring experiments or that the irradiation time needs to be prolonged.
- the gamma heating is decreased (due to the local thermal neutron flux depression) and many experiments use gamma heating in order to heat the experiment to a relevant temperature. The screen may therefore influence the temperature of the neighbouring experiments.

2.4 Simulation of phenomena involved in the transmutation process

In the previous section it has been concluded that a neutron spectrum can be tailored to a significant extent to simulate FR-conditions. The increase in the irradiation costs and the very limited availability of fully shielded facilities makes that it must be carefully assessed if irradiation in a shielded facility is strictly required.

It is not the neutron spectrum which is of importance to the experiment, but derived parameters such as, for example, Displacements Per Atom (DPA) for materials irradiations, the radial temperature and burnup profile (caused by the radial power profile) in case of fuel irradiations and the defects induced by fission products and He generation in case of fuel microstructure evolution studies.

An analysis has been made to identify key parameters involved in the transmutation process and for some of them, how to simulate it. For the quantification of the neutron spectrum and of the parameters linked to neutron physics (local BU and He production), specific computation tools have been

developed and qualified in order to analyse precisely the local irradiation conditions in MTR and to compare them to power reactor cases.
Few examples of possible experimental simulations are given below.
By optimizing the MTR irradiation conditions (Linear Heat Generation Rate and cladding temperature), it is possible to simulate the temperature profile within the pellet in spite of a power density profile significantly different between fast reactors and MTR. Indeed, in water cooled MTR, the power density at the pellet edge is significantly higher than the power density in the centre of the pellet. This radial variation in power density is nearly absent in FR's.
By adjusting the ^{235}U enrichment, the Am content and the neutron flux in the pellet, it is possible to simulate in MTR irradiation, the evolution of the fission rate and He generation in the transmutation targets. He production can also be provoked in some experiment by adding boron.
From the above discussions it may be concluded that exploratory FR-fuel or FR-transmutation targets studies might be performed without full neutron screening. Successful examples of such irradiations without neutron screening are the EFTTRA-series of irradiations. These irradiations are being used to get a basic understanding of the phenomena that takes place in these advanced fuel.
A further very important aspect in the irradiation of FR fuels or FR transmutation targets is that the irradiation should be performed under very well characterized conditions, preferably with instrumentation such as thermocouples and pressure transducers in order to gain detailed information from the irradiation. MTRs offer suitable conditions to achieve well characterized and instrumented experimental conditions.

2.5 Power transient

Extensive power transient test programs on PWR and BWR fuel have been performed in the past. Nowadays such tests are still strongly needed for the qualification of new fuel designs, for the qualification of existing fuel designs at high burn-up, for reducing the number of in-service fuel failures and as a support of research programs on global fuel performance or focussing on specific phenomena occurring in fuel (e.g. fission gas release).
For all these applications, transients test facilities should offer a wide variety of characteristics. Transients with large amplitude, even on depleted fuel, should be possible, with a wide range in maximum and minimum power level. They should be reproducible in order to compare various fuel segments in identical conditions. The facilities should offer representative coolant conditions. They should be equipped for loading of re-fabricated and instrumented rods. Though generally the tests are not aiming at testing accidental scenarios, the systems should be fuel failure tolerant. The linear fuel power is a very important parameter in these types of tests, so an accurate on-line linear power determination during the transient is of crucial importance. The fuel power should be sufficiently homogeneous as well (axially, radially and circumferentially).
Various irradiation device technologies have been used in the past, some of which are still in operation: moving devices like the displacement system in the OSIRIS reflector, systems using a neutron absorbing gas screen at variable pressure (^{3}He or BF_3), systems making use of fast variations of the overall reactor power or combinations of these techniques. The existing fuel power transient systems were evaluated and found to perform very well, each with certain limitations.
The on-line power determination procedures applied in the existing systems was analysed in detail: although some complementary techniques were identified, making use of the monitoring of nuclear field parameters (self powered neutron detectors, miniature fission chambers, various miniaturized gamma sensors), the thermal balance method was confirmed to be the only viable way for the absolute on-line power determination. In this method, the differential temperature monitoring is the main

parameter affecting the uncertainty in the final result, so possible improvements in this measurement were proposed.
A new concept for fuel power transient device was developed at SCK•CEN. It combines two technologies: a variable neutron absorbing screen based on a boric acid solution with variable concentration (the VANESSA device) and a rotational movement through a large flux gradient in a 200 mm diameter channel of the BR2 reactor (the RODEO device). Figures 4 and 5 illustrate both concepts. In the conceptual design study, design choices for both systems (in-pile and out-pile) were made based on thermal and thermohydraulic considerations and the power transient capabilities were investigated (achievable lower and upper power limits; power ramp rate). Moreover, waste and activation issues and general safety aspects were treated, the required instrumentation was defined and testing/calibration procedures were elaborated. Finally, the achievable boiling conditions in the pressurized water capsule were assessed and the on-line power determination procedure was defined.
As a result of the study (mainly dedicated to BR2 environment), a combination of both systems (RODEO and VANESSA) was proposed as the reference configuration. The VANESSA device will be used for adjusting the base power level (about a factor of two power adjustment range), while the execution of the transient itself will be done with the RODEO system, which can provide up to a factor of four power increase in a few seconds with controllable ramp profile.

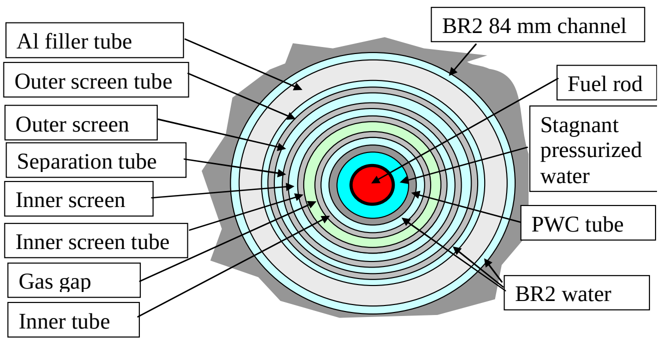


Figure 4 : Horizontal cut of the VANESSA device, including the pressurized water capsule with the fuel in stagnant water, the cooling water (also used for the thermal balance measurement), the thermalscreen (stagnant helium), the variable boric acid neutron screen (downward and upward flow) and the external cooling of the system

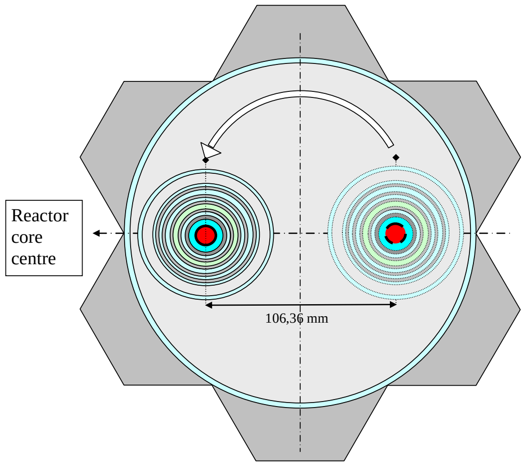


Figure 5 : Horizontal cut of the RODEO device in a 200 mm BR2 reactor channel, loaded with VANESSA.

2.6 Water chemistry

In-core water chemistry conditions are directly related to the important issues about material integrity, radioactivity transport and build-up as well as fuel efficiency. Therefore, development of reliable water chemistry control in-core is essential for present as well as next generation LWRs. In this work some dedicated issues related to in-core water chemistry measurement have been addressed. In particular, the current state-of-art experiences of in-core electrochemical measuring techniques and other water chemistry control techniques have been summarized and discussed. Some new dedicated issues such as radiation induced electromotive force (RIEMF) and high power heated rod have been addressed. Moreover, a new concept of noble metal reference electrode for the application in more oxygenated water environments and application of an innovative in-pile mobile reference electrode have been introduced and described in details. Finally, a new water loop design is proposed to meet the need of some new applications in MTR such as Axial Offset Anomaly (AOA) investigation.

2.7 Fission gas measurement

Quantitative measurement of stable or radioactive isotopes released from an irradiated fuel sample provides important information on the mechanisms controlling the migration of Fission Products (FPs) inside the fuel microstructure, and their release out-of the fuel (under normal and off-normal situations).
For that purpose, specific measurements can be made in MTR experiment, mainly by monitoring a fluid circulating in a line connected to the irradiated sample. Two different strategies for the FG measurement are available: radioactivity counting or atom counting (the only technique for stable and long-lived radionuclides).
The European teams (NRG, ITU, PSI, IRSN and CEA) specialized in on-line or delayed measurement of fission products, and in particular gases, highlighted reference techniques (Gamma spectrometry, Alpha spectrometry, Beta counting, Delayed neutron detection, Gas mass spectrometry, Inductively Coupled Plasma Mass Spectrometry) with associated measurement range and identification of interferents. The group elaborated a set of recommendations on fission product measurement techniques which must (or shall) be implanted in a modern Material Test Reactor (MTR), either in a fission product laboratory (mainly related with on-line measurements) or in a radio-chemistry laboratory (off-line)
The group also worked on the implementation of an innovative fission gas concentration monitoring on a running MTR fuel experiment, as a demonstration process: the choice was made of an on-line Gas Mass Spectrometry (GMS) technique and of the experiment (EU1 HTR fuel experiment in HFR).
This work led to a technical and financial report with the pre-calculation of the expected Fission Gases (FGs) concentrations in the sample sweeping line, the choice of the suitable mobile GMS model, the definition of the experimental protocol, liability management, result and apparatus use rights and financing plan. Nevertheless, the GMS cost and the delay on EU1 re-starting date led to cancel the manufacturing and test of the sampling and measurement device.

2.8 Qualification of electronic modules under neutron and gamma irradiation.

In a MTR reactor pool the devices are situated at various locations and connected to the out of pile area via fluid and electrical lines. These connecting lines are long and difficult to operate during the reactor shutdown phases (disconnection/reconnection, loading/unloading and transfer operations on the device). In order to limit those operation issues, exploratory studies are performed in order to reduce when possible the electrical connections going out of the core and the equipments located in the out of pile part. One solution being explored is to increase the integration of sensors and actuators in the irradiation device itself and to multiplex electric signals in order to reduce lines while possibly increasing the number of signals being processed. Suppressing connections using wireless connection modules is also under consideration for simpler devices when there is no safety signal being processed.
Hence various electronics systems along the measurement chain could be in the near future placed in some neutron and gamma irradiation and their behaviour should be checked against their irradiation resilience because a correct shielding is not often possible due to space or loading constraints.

Gamma dose rates received by electronic boards could be of two types:

- Steady dose rates coming from the core over a long period. In that case, the electronic modules placed in the extension of the devices or other systems located in the reactor pool are submitted to steady gamma dose rates and to a lesser extent to some neutrons dose rates. A test of irradiation resilience over the estimated lifespan of the device (5 years equivalent full power) should be carried out to make sure of the robustness of electronics. The corresponding integrated gamma dose is about 15kGy.

- Peak dose rates when a device is loaded off the core. This can generate a gamma flash on a sensitive part of another device. The corresponding gamma rate is estimated to be about 6.4kGy/h for one minute.

After a collective survey of services possibly offered by each reactor, the Instituto Tecnologico e Nuclear (ITN) promotes the Portuguese Research Reactor (RPI) as a Centre for Electronics selection advice, board design expertise and irradiation purposes.
Two major irradiation facilities are available at ITN: the RPI research reactor (figure 6) for mixed neutron and gamma irradiation and an industrial Co60 source for pure gamma irradiation.
The RPI reactor has an irradiation chamber (figure 7) that has been developed for the on-line testing of larger electronic modules with a fast neutron flux up to 5 10^8 n/cm²/s with a simultaneous gamma dose rate up to 50 $Gy.h^{-1}$.
The industrial Co60 source is capable of gamma dose rates up to 10 $kGy.h^{-1}$ .That would allow a first selection of suitable boards and study of radiation bursts.
The irradiation chamber, set at the end of the so called "beam tube E4" consists in a 15cm diameter and 100cm long tube placed inside a 100x60x60cm^3 cavity. Various shields/filters of lead, cadmium, polyethylene can be installed to adjust for the irradiation features. The Complutense University of Madrid (UCM) can be associated for preparation and interpretation phases of the tests.

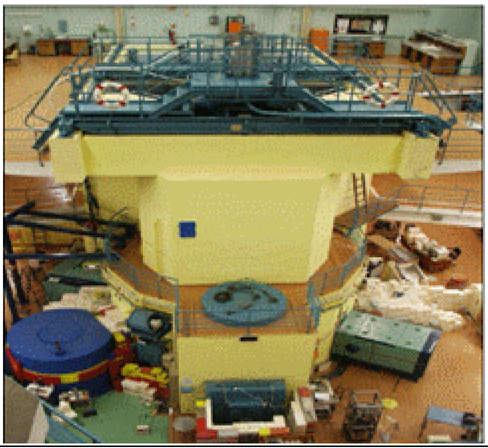


Fig.6. Overview of RPI reactor

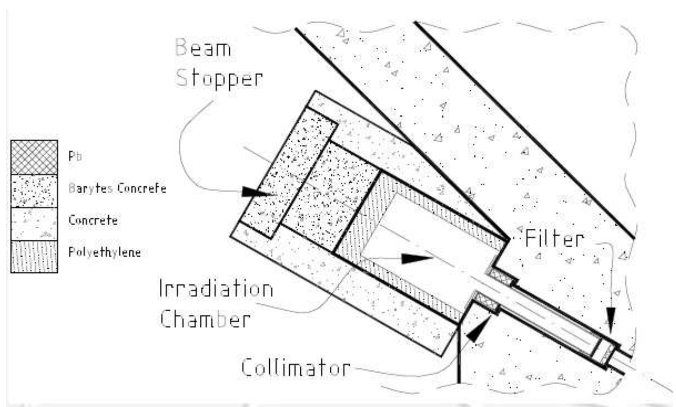


Fig.7. Description of the irradiation cavity at ITN

As examples, the test platform being set up will cover electronic modules testing such as temperature measurement instrumentation, A/D converters, microcontrollers and RF transmitters, multiplexing system, as a single module or in different application boards; for irradiation test devices but also for neutron imaging system.

2.9 Materials behaviour

During normal operation of LWR the fuel cladding tubes experience variable and multiaxial thermo-mechanical loading sequences due to fuel behaviour and pellet-cladding interactions. Modelling of fuel performance and safety assessments require more reliable mechanical data on cladding tube behaviour, e.g., irradiation and thermal creep behaviour under multiaxial stress state and stress relaxation behaviour. It is also noted that interpretation of mechanical properties of Zirconium is complicated by the fact that cladding tubes are strongly anisotropic due to hexagonal crystal structure and texture induced by manufacturing process.

New innovative instrumented pressure tube tests have been developed by VTT, CEA and SCK.CEN in the framework of MTR+I3 project, which allow on-line strain measurement under controlled and variable uni- or biaxial stress state. Two prototype loading devices have been developed, e.g., uniaxial tensile device with two legs open tube specimens for low stress levels and biaxial stress device with pressurised tube specimen for high stress levels.

The basic principle of both creep test devices is based on the use of a pneumatic bellows to introduce load and a linear variable differential transformer (LVDT) sensor to measure the resulting displacement produced in the test specimen. Two bellows with outside diameter of 7 mm were mounted inside the double legs specimen. The applied bellows pressure of 120 bar introduces a load of 300 N corresponding to a stress level of about 20 MPa in the double legs specimen. Due to limited space available inside the double legs open tube specimen the achieved stress level is limited to relatively low levels.

The biaxial creep test device with pressurised tube specimen utilises both independently controlled internal pressure and external pneumatic bellows to introduce controlled biaxial stress state. The resulting axial and diametric strains are measured by linear and 3-point contact diameter LVDT sensors. The external bellows introduce a tensile load of about 2500 N which allow controlling the stress biaxiality ratio σ_{ax}/σ_{cir} depending on the applied internal pressure. It is also noted that both internal pressure and external load can be varied and controlled during the experiment. The schematic design of the uni- and biaxial creep test devices is shown in Fig. 8.

The above described prototype devices developed in the MTR+I3 project served as a basis for bilateral agreement between CEA and VTT to initiate an irradiation experiment called Melodie in OSIRIS material test reactor. The basic function of the Melodie device is to carry out in-reactor creep test with online strain measurements under controlled biaxial stress state with variable stress biaxiality ratio σ_{ax}/σ_{cir} between about 0 and 1. The external axial loading part is modified with double bellows in order to introduce both axial tensile and compressive loads needed, e.g., for pure circumferential stress state in the pressurised tube specimen. To accommodate the Melodie device and the necessary instrumentation to perform the biaxial creep test in the OSIRIS reactor, a CHOUCA type irradiation rig with a special specimen holder will be applied. The experiment will be performed in NaK and the target temperature is around 350°C.

Lifetime management of LWRs have identified irradiation assisted stress corrosion cracking (IASCC) as an important ageing mechanism of reactor core components. The stress corrosion cracking phenomenon typically consists of an initiation stage and a propagation stage. The propagation stage is most studied, as the material exhibits a more deterministic behaviour in this type of test. However, the crack initiation stage may take up most of the components lifetime and initiated cracks may lead to fast failure and early replacements of components. An advanced stress corrosion cracking testing requires a mechanical loading device (in order to provide the required stress and strain in a controlled and stable way) and instruments for online measurements on load/strain and cracking process. An additional value is offered by water chemistry measurements and corrosion property measurements which specify the environmental condition and material response.

VTT and SCK.CEN have developed experimental loading devices based on pneumatic bellows for both crack initiation and propagation type of tests. The former utilises compressive loading with ring shaped specimens and the latter tensile loading with DC(T) type specimens. The loading devices are instrumented by LVDT probes for displacement measurements, electrochemical noise method for crack initiation and potential drop method for crack propagation measurement further developed by PSI and CEA. Figure 9 illustrates the loading devices developed for crack initiation and propagation tests. Additional electrochemical methods to specify the environmental conditions have been developed by Studsvik, AEKI and UJV.

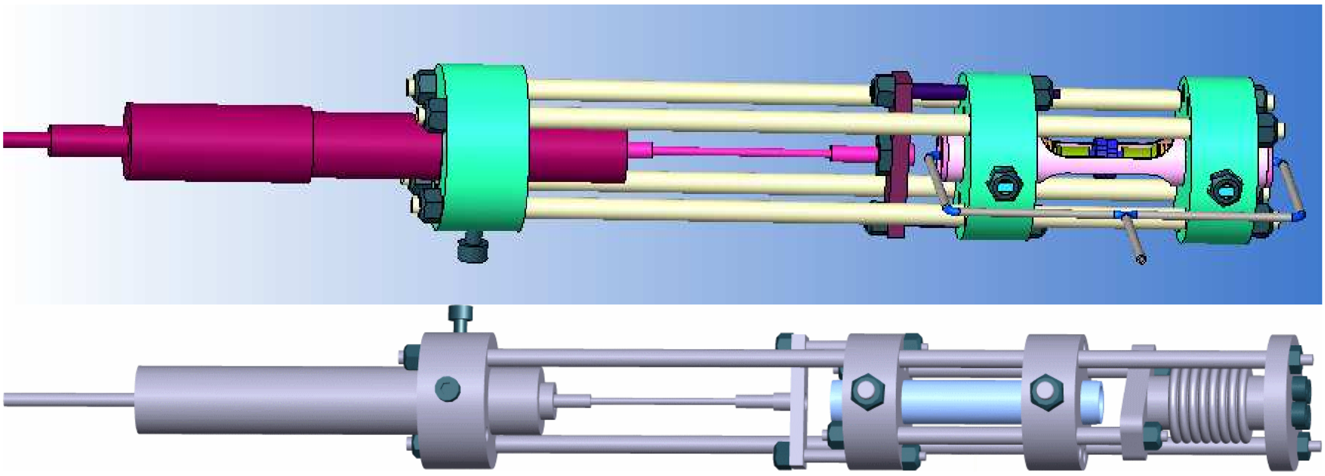
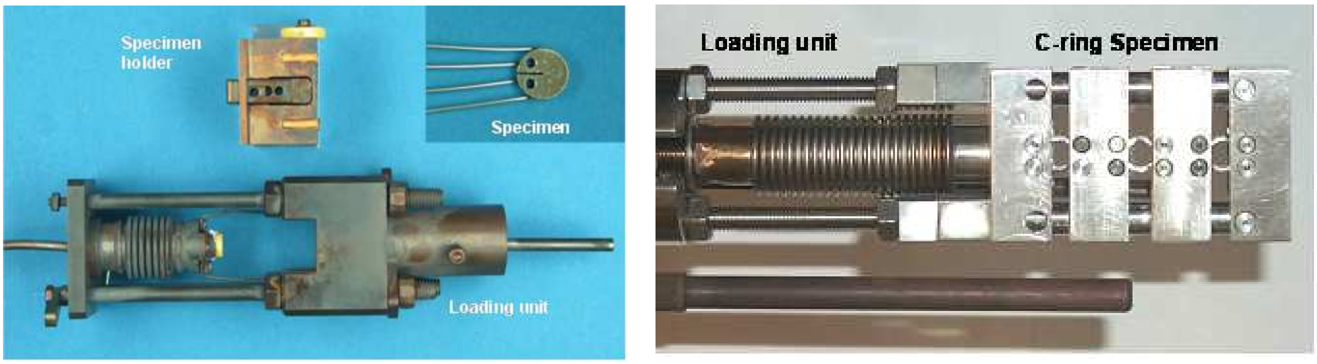


Figure 8 : Schematic picture of uni- and biaxial creep test devices with two legs open tube and pressurised tube specimen.



Figures 9 : Loading devices for stress corrosion crack initiation and propagation studies.

2.10 Gas loop technology

The studies devoted to gas loop technology development started with the identification of “high temperature material testing needs”. Within this framework, materials usable in the area of VHTR (Very High Temperature Reactor) and conditions for their usage were identified. An analysis of experimental methods for the area of VHTR and of their usability in high-temperature irradiation loops was conducted, as well as a usability analysis of HTR materials databases. Steps were also taken to consolidate procedures across Gen-IV.

The second steps dealt with “high temperature gas loop component development”. It was initially focused on the transformation of requirements from the first study into specific implementations in high-temperature irradiation loops. An analysis of loop prerequisites was conducted, and critical locations identified: the irradiation channel, compressor, cleaning and dosing.

The situation regarding a circulator for the VHTR loops is challenging; it can be said that no standard product usable in these loops exists. Two different circulator designs were analyzed and tested at CEA and UJV. In cooperation with Czech manufacturers, UJV developed a radial compressor, and CEA developed a compressor of a different type (side channel compressor) that is more suitable for low flow rates and a large pressure differential (see figure 10 and 11).

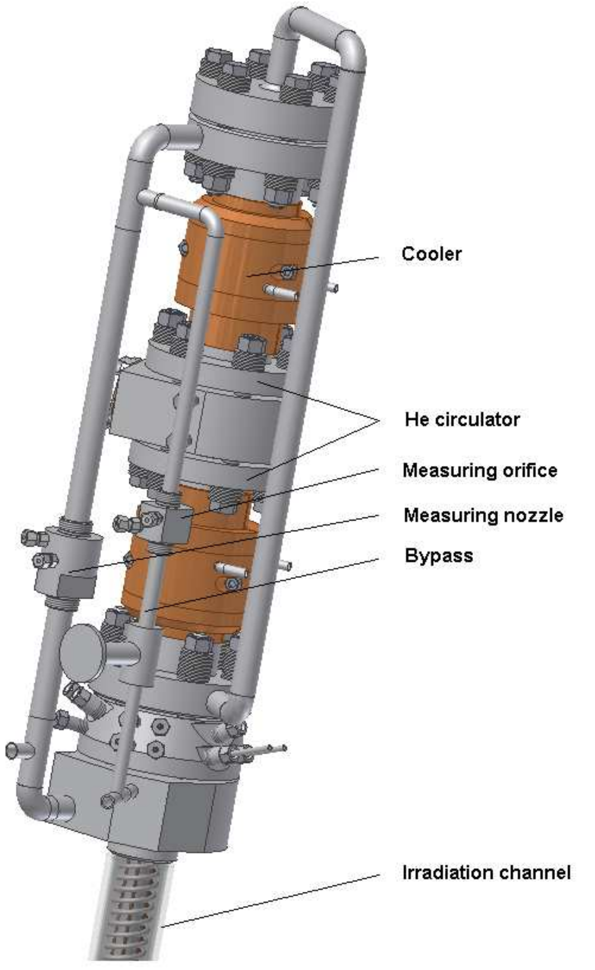


Figure 10 : Radial compressor (UJV)

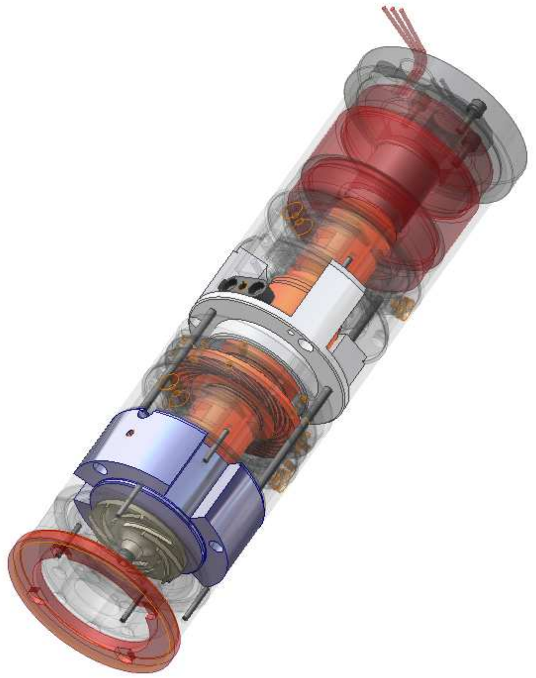


Figure 11 : Side channel compressor (CEA)

A basic analysis and classification of heat exchangers types was also performed. For experimental loops, the most suitable design appears to be a standard tube exchanger. For this type, CFD optimization of gratings was also conducted (see figure 12).
A number of analyses and experiments were conducted in the area of dosage and purification systems; the scope was broadened to include chemical analysis, as it is of course necessary to control the dosage and cleaning. The purification columns are shown on the figure 13.

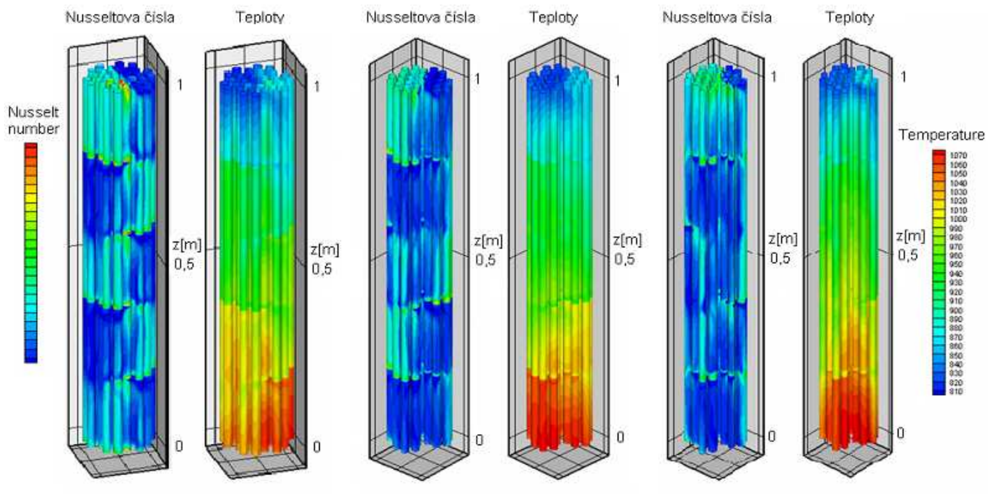


Figure 12 : CFD optimization studies

Figure 13 : Purification columns

2.11 Heavy liquid metal loop development

This section concerns the development of an in-pile Heavy Liquid Metals (HLM) materials test loop for BR2.
The technology of heavy liquid metals is used in various sections of applied nuclear science. These include nuclear energy production and radioactive waste management in e.g. the Gen-IV Lead Fast Reactor and liquid metal cooled accelerator driven system. Heavy liquid metal technology is also found in facilities for research applications like e.g. spallation neutron sources. The common feature in these applications is the nuclear aspect.
The research in existing laboratories mostly covers lead and Lead-Bismuth Eutectic (LBE) technology, thermal-hydraulics and material research using various experimental set-ups involving liquid lead alloys. However, the actual conditions in nuclear systems involving lead alloys are a combination of radiation, corrosion and erosion, liquid metal embrittlement and mechanical and thermal stress. A major lack in the capabilities of the existing facilities is the almost complete absence of experiments combining HLM and radioactive materials/environments. At present such experiments have only been conducted in the LISOR facility (where materials are irradiated by a 72 MeV proton beam in a LBE loop) and in the STIP programme (where materials have been irradiated in LBE and Pb using the SinQ target), both at PSI. In addition at SCK•CEN experiments with lead alloys in radioactive conditions have started with the construction of an LBE autoclave in a hot cell. Materials irradiation in stagnant LBE using the BR2 reactor in Mol (B) and the HFR reactor in Petten (Nl) are carried out in the framework of the FP6 IP-EUROTRANS project.
Within the MTR+I3 project a high temperature HLM loop for use in the existing MTR BR2 at SCK•CEN is being designed (figure 14). The design is based on the experience that is gained from the

development of the stagnant LBE irradiation rig ASTIR at BR2 and the existing out-of-pile loops for the selection and qualification of essential components.

The HLM loop will consist of three concentric cylindrical structures. The outer two cylinders create a double walled, helium filled gap in between the cooling water of the reactor and the LBE volume as required by safety regulations. The third cylinder ensures the separation between the LBE inflow and outflow. The loop is divided in a test section, a heat exchanger, a pump, an oxygen control system, an expansion volume and a gas pressure control system. The test section will include a volume where material samples and components can be exposed to the combined effect of radiation and HLM flow. The entire test section is heated by the gamma radiation in the core. This heat will be removed by radial heat loss to the reactor core cooling water, which has a temperature of 50 °C.

The experimental section of the HLM loop needs a high fast neutron flux. This is achieved by placing the test section inside a BR2 fuel assembly. The BR2 reactor is a light water cooled MTR in which neutrons are moderated by a beryllium matrix and partially by the cooling water. A standard fuel element is made of six concentric fuel plates, consisting of an aluminium-uranium cermet core with highly enriched (70 to 93 %) uranium, clad with aluminium alloy sheets. The outer dimension of the experimental section inside a standard BR2 fuel element is limited to 25.4 mm, which is very small. However, it is possible to use modified fuel elements with only five fuel plates in the centre of the assembly. In this type of fuel element, the maximum outside diameter of the experiment is 34 mm. The advantage of such a configuration is that a larger volume is available for the experiment, at the cost of a slightly lower neutron flux (about 90% of a normal BR2 fuel assembly). This results in an induced radiation damage at the sample position of about 0.5 dpa per reactor cycle, which is corresponds to 2.5 dpa per year. The space available for the samples is 13 mm in diameter and 70 cm long and is located along the axis of the innermost cylinder, which also takes care of the outflow of the LBE from the test section.

The pump should be able to deliver HLM flow speeds of up to 2.5 m/s at the sample position and should compensate for any pressure loss in the loop. This corresponds to a pressure of about 5 bar at 0.5 l/s. In order to avoid the use of any moving parts within the in-pile loop, an electromagnetic pump (EMP) has been chosen.

Due to the inherently low efficiency of an EMP in the case LBE, between 5 and 10 kW of heat will be dumped in the HLM passing through the pump. Apart from that, the gamma radiation in the core will produce about 45 kW of heat in the test section. About half of this is lost by radial heat transport to the BR2 cooling water passing along the test section. In order to remove the remaining heat caused by gamma radiation and the heat produced by the EMP, a heat exchanger section is foreseen in between the pump and the test section. In this section, again heat is lost by radial heat transport from the LBE through the helium filled gap to the BR2 cooling water. The helium gap is very narrow at this position. By modifying the pressure of the helium gas (in partial vacuum condition), the efficiency of the cooling can be changed, allowing for an effective regulation of the LBE temperature. In case of shut down of the reactor and at start-up of the experiment, heaters are foreseen along the loop to keep the LBE in a liquid state.

The loop will be equipped by a large number of thermocouples, checking the temperature of the LBE at different positions along the loop and monitoring the temperature of the samples. A flow measurement is foreseen in order to guarantee the required HLM flow speed at the sample position. Oxygen measurement and control will be located in the expansion volume of the loop.

At the present, the conceptual and engineering pre-design of the HLM loop for BR2 has been completed. A safety analysis of the proposed design is ongoing and waste handling and disposal are being studied.

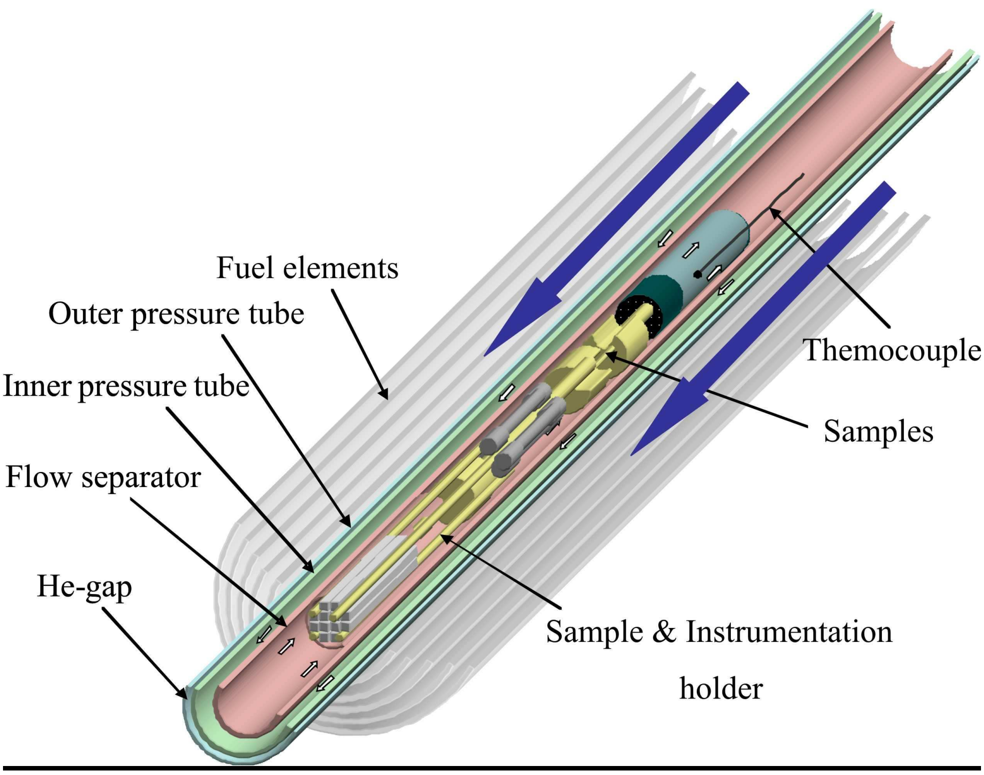


Figure 14 : Schematic view of the HLM loop test section

2.12 Safety test measurements

The goal of this study in the frame of the MTR+I3 project was to gather and federate the know-how of European engineering in nuclear experimental facilities in the field of safety test instrumentation, to identify most relevant required instrumentation to develop and to make some proposals and tests of innovative instrumentation, in order to anticipate and identify the future needs for safety experiments
The first step of the study was the determination of the “most important” sensors to develop short or medium term. Criteria of importance to be considered are : safety issues concerned ; modelled physical phenomena ; relevance of the measurement of the physical phenomenon considered ; and feasibility of the technology used for measurement.
A specific methodology has been used to quantify the importance, relevance and feasibility of each item in order to select the “best compromise” from concerned safety issue until its technical feasibility.
Firstly the four fields of interests were described. Information comes both from bibliography (authorities and institutes of safety) and interviews of experts.

A - Safety issues remain numerous. However, it quickly appeared that the limitation to LWR system and to tests requiring a neutron flux for the physical phenomenon representativeness lead to safety issues of LOCA (Loss of Coolant Accident) and RIA (Reactivity Initiated Accident). Only these two cases are considered in the following study.

B - The physical phenomena were described according to their three main locations: the fuel (energy destocking, fission gas release, expansion, relocation and dispersion), the cladding (oxidation, spalling, embrittlement, deformation and failure) and the coolant (coolability and clad to coolant heat transfer).

C - Measurements important for scientists are listed with the same location description as physical phenomena: the fuel (measuring its inner and surface temperature, pressure, gas production, motion, mass dispersion and grain sizing) ;the cladding (measuring its inner and surface temperature, radial and axial deformation, oxidation thickness, spalling size) and the coolant (measuring its temperature, pressure, flow, time and space dry out, void fraction and gas).

D - Lastly, the technological aspect was graded according to coefficients of feasibility on the previously identified measurements taking into account specificities of safety tests (in particular kinetics, which are very different between LOCA and RIA tests).

All the items were quantified according to a weighed notation, with arguing among experts. This methodology allows identifying two instrumentations of major importance:

- the cladding surface temperature: the outer surface temperature of the cladding gathers a good compromise between scientific interest and technical feasibility. Welding techniques must be qualified and the demonstration showed that swelling or failure of the cladding are neither promoted nor prevented by welding (figures 15 and 16).

- the internal rod pressure: despite a long practice on experimental devices in all MTRs, this measurement revealed some chronic drawbacks, depending on technology, such as the need for umbilical cable, a long response time, a drift under irradiation or a bad lifetime.

Surface cladding temperature

Rumanian institute of INR at Pitesti had formerly carried out such instrumentation by welding thermocouples (TC): the project represented an opportunity to implement this competence again. Specific weld tests of the TC wires by microplasma were carried out and this hot spot was then welded by resistive technique. Analyses showed the repeatability and the firmness of this welding.

In addition, a facility allowed testing pressurized cladding samples with welded thermocouples under a temperature transient close to LOCA conditions (initial pressure and temperature of 4 MPa and 300°C). Tests of ballooning and burst (figure 17) showed that on fresh cladding, this type of welding even close to the deformation zone does not skew the physical phenomenon. Tests with hydrided cladding showed feasibility in terms of welding, but other tests would be necessary to show the harmlessness of the welding with respect to the mechanical behaviour of the hydrided cladding.

The continuation of this work could be the study of tools for a welding in hot cell (on irradiated cladding), the tight routing of thermocouple wires and the thermal calibration of welded thermocouples (by pyrometry for instance).

		
Figure 15: hot spot welding	Figure 16: thermocouple wires welding on cladding	Figure 17: Burst test result

Internal Rod Pressure

Belgian institute SCK•CEN of Mol dealt with the study of internal rod pressure according to two aspects:

- the experience feedback of internal rod pressure measurement, in particular the LVDT technology (figures 18 and 19) pointed out in the former theoretical step. This synthesis included unpublished irradiation tests of sensors in BR2 (Mol).
- the design of a prototype aiming at sensor calibration to adjust the drift (figure 20).

The results of this study show a partial knowledge of LVDT behaviour under irradiation. Specific tests (fast/thermal flux, ferromagnetic core in various materials) would allow a better prediction of LVDT drift. The prototype proposed by the SCK•CEN takes up the well known technology of institute IFE Halden again by duplicating the bellows and supplying an external gas for calibration. All the procedure of calibration is studied to reach the correction of drift and in fine a more accurate measurement.

The conclusions of this work confirm the very strong advantage of LVDT sensor not only for the pressure measurement but also for many other measurements using the LVDT technology. Preliminary work must be continued by the realization and the qualification of the proposed prototype and by an improved signal processing, these hardware and software approaches being complementary, and following studies must be carried out in a better characterization of the drop of permeability of materials under irradiation.

Figure 18 : available and tested (in BR2) LVDT pressure sensors

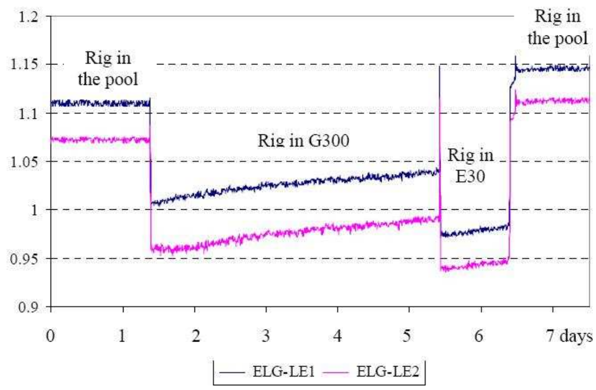


Figure 19 : LVDT signals in BR2 tests

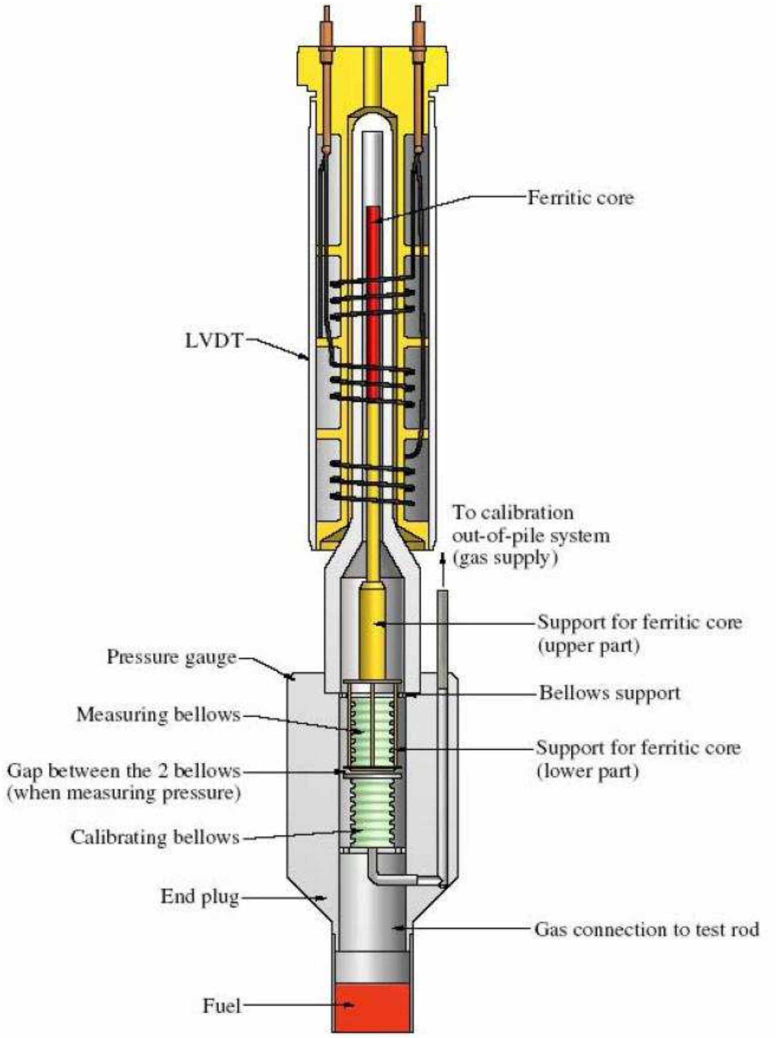


Figure 20 : Prototype design

As a conclusion, to address the very wide issues of the necessary developments in the field of safety tests instrumentation, an original and methodical approach led to determine two relevant tracks of development so much for safety issues and the models of scientists as the measurement and the technology of experimenters. It appears that fundamental measurement (temperature of surface fuel cladding and internal rod pressure) are more than ever necessary, with requirements of increased precision and non intrusivity. Beyond the information exchange on embedded instrumentation in MTR, the revamping of fine welding and the study of an innovating sensor's prototype, this work exposed some R&D tracks to be carried out in short-run. Lastly, the other measurements, quoted in the study, would be relevant to develop mid-term, in particular the use of the optical fibre that by various principles of measurements reaches multiples measurements with the major advantage of non intrusivity.

3 TRAINING

Beside the technological aspects, MTR+I3 also focused on establishing a European research reactor training network involving a variety of research reactors.
Within the network of MTR+I3 partners, a number of research reactors may be used for training purposes. These reactors differ in design, location, power level and training facilities. Therefore, a broad range of training possibilities was provided (TRIGA Reactor operated by ATI, Vienna, Austria; BR1, VENUS and BR2 research reactors, operated by SCK.CEN, Mol, Belgium; Nuclear Research Reactor LVR-15 operated by UJV, Rez, plc., Czech Republic; ISIS, operated by CEA, Saclay, France; GRR-1 Research Reactor operated by NCSR -D, Aghia Paraskevi, Greece; and RPI, operated by ITN, Sacavem, Portugal)
This network activity was structured in several steps:

- The target groups for training and assessment of the number of potential candidates per year were determined. Target groups were research reactor operators, experimentalists using the facility, irradiation device designers, reactor supervisors, reactor managers, students of nuclear physics etc.
- The training programs to the particular needs of the various target groups in the most appropriate partners institutions were defined. New training sessions dedicated to the MTR needs were developed using existing programs in order to attract young persons in the MTR field (taking into account the various training programs presently carried out in education and training centres within the European Union)
- The first training sessions to targeted groups started in spring 2009. The 2009 sessions are described below:
  - Austria-ATI: Practical Model Training Course for Research Reactor Operators
  - Belgium-MOL- SCK.CEN: Training Course on Irradiation Devices & Operation and Reactor Physics Experiments
  - Czech Republic-Rez: Program of the MTR operators and experimenters training course focused on preparation of water loop experiments
  - France-INSTN: Principles and Operation of Nuclear Reactors,
  - Greece-NSCR-D: Computational Nuclear Technology,
  - Greece-NSCR-D: Training Course on Reactor Core Neutronic Analysis Codes
  - Portugal-ITN: Technical Course on Neutron Spectrometry via The Multiple-foil Activation Method,
  - Portugal-ITN: Technical Course On Reactor Instrumentation and Control,

These courses have been especially developed for the MTR+I3 project and attracted students and nuclear staff from all over Europe. As these courses had a very positive impact on the nuclear community, dedicated follow-up courses are planned even after the end of the MTR+I3 project.

4 CONCLUSION

MTR+I3 improved existing European MTR services and prepares the next generation of research infrastructures by enlarging the MTR community, improving networks, supporting joint technological developments, and optimising the use of existing MTRs . It overcomes the present situation of fragmented resources and low investments in hardware and competences and reinforces existing European experimental capabilities.

This will boost Europe's strategic capacity for safety, plant life management and economical optimisation of existing and future power plants, innovative fuel & material developments for future reactors including less waste and better use of resources. This long-term initiative also helps to attract a young generation of scientists and engineers to become future European experts and managers.

This paper illustrates the broad scope of innovative irradiation technologies which meet strong operational and scientific interests. The technologies investigated in MTR+I3 are to be considered as mature enough to be implemented in present and coming MTRs. The assessment of each investigated technology took benefit from the exchanges between several European institutes among the MTR+I3 partners. Nevertheless, subsequent development steps will require large investment cost and detailed specifications that can be provided in very specific projects. These projects have to be built first by small core-groups of partners (research lab, end-users) sharing, through dedicated agreements, operational objectives, intellectual property, costs, strategy... Such initiatives have been made possible owing to the 5th and 6th Framework Programme subsequent collaborative projects which have contributed to build up a European Community in the material and fuel irradiation domain.

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ENEN (http://www.enen-assoc.org/) European Nuclear Education Network

EMTR (http://www.emtr.eu/) List of the main European Material testing reactors

SNETP (http://www.snetp.eu/) Sustainable Nuclear Energy Technology Platform

MTR+I3 (http://www.mtri3.eu/) Integrated Infrastructure Initiative for Material Testing Reactors Innovations