

# Quantifying thermomechanical clad load mechanisms and incipient fuel melting of a LWR fuel rod under power transients

## The P2M Joint Project Proposal in the frame of the OECD/NEA

### Technical description

**Initiative launched by the core group: CEA / SCK•CEN / EDF**

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## 1. CONTEXT

The landscape of the irradiation infrastructures worldwide changed dramatically in recent years: large material testing reactors (MTR) such as the Halden Boiling Water Reactor (HBWR, NO), Japan Material Test Reactor (JMTR, JA) and OSIRIS at CEA (FR) each experienced a definite shutdown in June 2018, mid-2017 and the end of 2015 respectively. These events opened a period with reduced experimental capability for addressing needs in the field of nuclear fuel and materials development and qualification. Major MTRs (water cooled high power research reactors for fuels and materials testing) still in operation today are ATR (USA), MIR and SM3 (Russia), BR2 (Belgium), HFR (Netherlands), LVR-15 (Czech Republic) and there is up-to-now one new irradiation facility under construction; the Jules Horowitz MTR<sup>1</sup>. To overcome these uncertainties, and to preserve skilled staff and knowledge, an efficient way is to establish and maintain international collaborations through international joint research projects. One example among others is the case of the Halden Reactor Project (HRP), managed under the umbrella of the OECD/NEA, which demonstrated the value of such a synergy for decades. However, the closure of the HBWR has led HRP members to consider other joint projects in order to maintain this fruitful international cooperation. The goal is now to use several alternate facilities in parallel (i.e. MTRs and hot cell laboratories for post-irradiation examinations) to reduce the impact of a possible defaulting facility on the experimental programs.

In coherence with this view, the Jules Horowitz Reactor (JHR) Project has set up an International Consortium for close partnership between the funding organisations. This Consortium set up three

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<sup>1</sup> The Jules Horowitz Reactor (JHR) is a MTR under construction at CEA Cadarache (France) and foreseen to be in operation by the beginning of the next decade. Designed to be operated as an International Users Facility, it will reinforce the irradiation services offered in Europe and the link between the operating European MTRs (BR2, HFR, LVR-15...) for advanced experiments [1], [2], [3].

Working Groups in 2013, namely Fuel, Materials and Technology. They gather scientific representatives and experts from industry (utilities and fuel suppliers), research and international organisations. As a key output of these working groups, it has been decided that “pre-JHR” irradiation programmes of common interest should be defined, addressing generic scientific issues of interest for the whole MTR community.

These programmes are proposed for the coming years in existing MTRs and/or hot cell laboratories, according to their possibilities, before potentially continuing them in JHR.

The first in pile experimental programme, which has been recommended by the Fuel Working Group experts (and now called P2M), aims to determine and quantify the main physical phenomena activated during any type of “slow” power transients with potential incipient fuel melting. Such transients may generate moderate to high straining of the fuel cladding. This programme covers transverse R&D topics exploring LWR fuel rod behaviour in operating conditions (incidental and accidental) rarely covered before and for which a lack of data is obvious. Moreover, this programme has caught the interest of various potential partners: R&D organisations, fuel vendors, plant operators and Safety Bodies.

After recalling the initiatives launched by the NEA during the year 2018, this document describes in detail the P2M project proposal (scientific and industrial motivations) and suggests a first roadmap to be discussed during a dedicated technical meeting.

## **2. PRESENTATION OF THE NEW MULTINATIONAL PROGRAMME OF THE OECD/NEA**

### **2.1 The OECD/NEA Workshop held in January 2018**

The Nuclear Science Committee (NSC) of the NEA organised a Workshop titled “Enhancing Experimental Support for Deployment of New Fuels and Materials” in January 2018. This workshop gathered industry (utilities, fuel makers), regulatory bodies, technical support organisations, research organisations and experimentalists together in order to reach a mutual understanding of the requirements of the validation/qualification process for innovative fuel and to enhance the effectiveness of experimental programmes. Discussions during the workshop helped to identify multiple directions for international collaboration where the NEA can play an important role as integrator and central coordinator in several potential tasks:

- One of them was to form a group to prioritise needs for validation/qualification of new fuels and materials and establish a link between the needs identified and the experimental and modelling capabilities available. The NSC Bureau has endorsed this action. At the closing meeting of the NSC Expert Group on Accident Tolerant Fuels for Light Water Reactors (EGATFL), also held in January, it was decided to extend the group activity towards the identification and prioritisation of experimental needs for testing revolutionary accident-tolerant fuel (ATF) concepts, linking the needs with the corresponding available infrastructure.
- Another consensual conclusion of the workshop was to organise multi-lateral and multi-national experimental programmes for qualification/validation of evolutionary and revolutionary fuel/cladding concepts, including ATF, and structural materials. For that aim, representatives of industry and TSOs were invited to send the NSC expressions of needs and

interests for experimental testing of fuel and material. In addition, representatives of R&D and experimental infrastructures were also invited to send proposals for fuel and material testing programmes.

- Finally, and due to the HBWR situation, a proposal was made to urgently form a joint experimental project to test selected ATF concepts, with the aim to perform them in the HBWR and other research reactors, including those presented at the workshop.

At this workshop, a CEA presentation entitled “Some pending issues in nuclear fuel and in-core materials development for LWRs: experimental support for modelling and simulation”, detailed three R&D experimental programme proposals in the nuclear fuel domain, gathering irradiation in MTRs and/or examinations and separate effect tests in hot cells. The first one dealt with fuel behaviour under slow power transients that addressed fuel safety and flexibility under plant operation. This proposal was the primary structure of the current P2M program.

## 2.2 The OECD/NEA Workshop held in October 2018

This workshop, gathering NSC and Committee on the Safety of Nuclear Installations (CSNI) members, was the first one held after the HBWR closure, and provided the basics of a new vision for building multilateral programmes. In particular, involvement of stakeholders to oversee the transition from the HRP to a new framework was underlined. It was confirmed, that international joint projects are the best way to ensure a continuity of coordination and cooperation in the use of experimental facilities to meet the needs of the community. Considering budgetary capacities, it is relevant to involve multiple test facilities that offer mutual benefit and advance the international vision for an integrated fuel and materials research.

A “core group” gathering three partners, SCK•CEN, CEA and EDF, presented the P2M proposal at this workshop. The aim is to launch a new ambitious NEA joint project based on a few advanced in-pile experiments.

The first task of this programme is to implement an irradiation programme in the BR2 MTR (SCK•CEN, BE). This choice is driven by the following benefits:

- the anticipated irradiation device is available off-the-shelf and fully operational
- BR2 exhibits a high neutron flux (for achieving a high terminal linear power on a high burn-up experimental rod)
- SCK•CEN experienced staff has already implemented similar tests.

The proposed irradiations will be supported by pre-test and post-test simulation, and completed by non-destructive and destructive PIEs in hot cell Laboratories (LHMA at SCK•CEN and LECA at CEA Cadarache).

The second task aims to test modern and innovative fuel and cladding materials (such as Accident Tolerant Fuel or Advanced Technology Fuel concepts). It will include the use of advanced irradiation devices and innovative on-line instrumentation.

Several positive features were highlighted, such as:

- the project targets clear and specific objectives
- it is going to explore margins for failure

- it is open to an extension, by testing a series of fuel samples, such providing relevant data to various fuel vendors
- it improves the experimental state-of-the-art with new techniques and instrumentation methods
- it offers an opportunity to develop new computational methods
- it is going to be a valuable driver to launch a new international framework.

### 3. OBJECTIVES AND INTEREST OF THE P2M PROPOSAL

#### 3.1 Scientific and R&D objectives

The in-pile experiment will focus on:

- fuel thermal expansion (due to the global temperature increase during the power transient)
- fuel gaseous swelling (due to increased diffusion of fission products and to the formation of gas bubbles, within the fuel grains and at the grain boundaries (see Figure 1 below))
- fission gas release (FGR) (due to temperature elevation and temperature gradient between the pellet centre and the periphery)
- supplementary FGR as a consequence of the phase change when fuel material starts to melt
- fuel volume change and its impact on the cladding in case the central part of the fuel pellet melts (that will imply very high linear heat generation rate (LHGR) levels).

This programme will combine several scientific objectives (with a view to enhance fuel behaviour knowledge during power transients) in one experiment such as:

- quantifying the FGR for high LHGR values and for fuels with high burn-up levels
- monitoring the clad deformation as a function of the loadings resulting from the physical mechanisms above mentioned
- defining the local irradiation conditions susceptible to generate a given quantity of melted fuel
- studying the impact of a partial fuel melted volume on the overall fuel rod behaviour and properties.

To achieve this, a specific in-pile irradiation test has to be defined to enable power transient test conditions slightly different from those of standard “power ramp” ones and covering, on a conservative approach, all the hypothetical situations.

The requirements on the test conditions are as follows:

- to investigate the individual effect of the above mentioned physical phenomena, the LHGR should be increased progressively
- to discriminate the investigated physical mechanisms, appropriate instrumentation should ideally be implemented for on-line data recording
- to reach, in a mastered way, the incipient fuel melting limit in the central part of the hottest fuel pellet(s) (i.e. at the maximum rod temperature plane), whatever the burn-up of the tested rod, the achievable Ramp Terminal Level (RTL) should be high enough
- to avoid the fuel rod failure, either during the power transient phase or at the occurrence of incipient melting, appropriate precautions should be taken
- to enable proper comparison of the tested rod before and after the transient, extensive non-destructive examinations (NDEs) should be performed before and after the test

- to reveal and understand the final microstructure of the material, detailed post-test destructive examinations (DEs) should be performed.

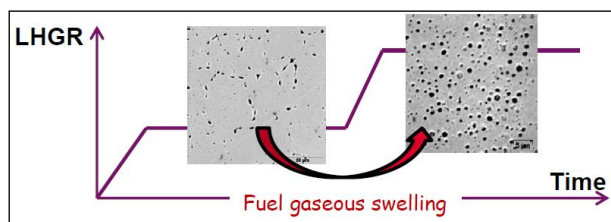


Fig. 1: Schematic of fuel gaseous swelling during a power increase

### 3.2 Improvement of modelling and codes on fuel rod behaviour

The current databases need to be updated to account for the advanced irradiation conditions targeted by P2M. Such conditions include high burn-up fuels, high LHGR levels, new fuels and modern cladding materials, including ATF products, properties change at the melting, etc... The experimental results will be made available to all the participants and will be used to update the fuel performance codes models.

As a matter of fact, modelling will be used to design the experiment itself to make it as relevant as possible. To define the test conditions and to specify the instrumentation performances (range, sensitivity...), pre-calculation of the fuel rod behaviour will be carried out to assess the evolution of the parameters of interest (centreline fuel temperature, anticipated incipient melting temperature, fission gas distribution, FGR, cladding strains, etc..) and detect potential thresholds.

These calculations will help to build the safety case of the experiment itself (this will be a specific task using validated models). They will also streamline the post-test comparisons between prediction and experimental results.

In turn, the proposed experiments will improve the members' fuel performance codes and models by enhancing their validation databases. Benchmarks between participant's calculation tools could be considered, therefore providing valuable feedback on models representativeness and ability to transpose test conditions to power reactor conditions.

### 3.3 Industrial motivations

Integral tests on nuclear fuel have always been valuable supports for safety demonstrations because they enable actual phenomena observation within a fuel rod during a transient. Hence, from a nuclear industry point of view, it is crucial to maintain the ability to carry out such transients in MTRs at a reasonable cost. This ability is now challenged as a result of the HBWR closure. One of the generic industrial motivation behind P2M is to promote a new international framework to perform new types of integral tests on a cost-sharing basis as an NEA joint project.

Because of the strong coupling between the various physical phenomena taking place within the fuel, separate effect experiments are insufficient to directly provide the requested safety margins. Integral or semi-integral tests are thus necessary. Various integral tests have been carried out in recent years, such as in-pile LOCA tests in HBWR (as part of the HRP) or in-pile RIA transients in CABRI (as part of the Cabri International Program (CIP)). Numerous power ramps have also been

performed to determine the PCI-SCC failure thresholds in test reactors such as R2 (Studsvik), OSIRIS (CEA) and HBWR, all of which are now shutdown. However, there is clearly a lack of updated data regarding slow power transients (leading potentially to incipient melting) impact on the fuel behaviour, as focus has been more placed on ramps testing. Regarding slow transients, the current fuel integrity demonstration relies on data derived from old tests, performed on obsolete fuel designs with limited (and not always reliable) instrumentation.

As a result, it is worth updating the database using modern fuel designs (fuel and cladding alloys) and comprehensive online measurements. The ultimate goal is of course to use these new data to update and improve the models of the fuel performance codes used for the safety analysis of the modern fuels.

### 3.4 P2M as a programme gathering crosscutting interests

The targeted scientific information gained from P2M will help to address safety and reliability issues related to flexible nuclear power plant (NPP) operation, fuel manufacturing and procurement processes:

- For R&D organisations: the project will enhance the overall knowledge of fuel and cladding behaviours; provide reliable data to validate fuel performance codes models; and extend international databases with updated experimental data in temperature/power domains where very few data exist, especially on modern fuel products.
- For utilities: the project will provide the maximal allowable cladding strain at high linear heat rate; the margin to incipient fuel melting; and, more globally, will improve the quantification of the available margins in the current fuel management schemes (the potential benefit being eventually a relaxation of the current limitations on in-reactor power change rates).
- For fuel vendors: the project will provide licensing data usable for new fuel products and for new fuel licensing methodologies and for safety enhancement (e.g. ATF products).
- For TSOs and safety organisations: the project will help to harmonise the safety approach methodologies.

### 3.5 Implementation of the P2M programme

The proposed project is divided into two tasks:

1. **The first task** should be started as soon as possible using the devices already available within the Core-Group (see section 3.2). It is proposed to update our general knowledge on the incipient melting of modern fuels and its impact on the fuel behaviour, as a function of burn-up (see reference [7] for the status of melting from the design point of view and the reference herein).
2. **The second task** will provide complementary scientific information by investigating the fuel rod cladding deformation during the transient caused by the fission gas and the solid and gaseous swelling of the fuel stack. Such a goal requires the adaption or development of a specific device welcoming specific sensors capable of measuring on-line the fuel rod diameter changes. The main interest in this experiment is to investigate, (i) the maximal total hoop strain the cladding can reach without failing; and (ii) the gaseous swelling kinetic over time and LHR (which is not very well documented).

Combining the results of Task 1 and Task 2 will result in an extended database on slow transient to help establishing the safety cases.

**The present proposal targets firstly Task 1, with a go / no go decision to continue with Task 2. In particular, the global financing scheme concerns only Task 1.**

## 4. PROPOSED PROJECT PLAN AND TEST MATRIX

### 4.1 General stakes

To implement the programme in a timely manner and without extensive and costly adaptation of the irradiation equipment, a two phase approach has been proposed:

1. implement the first experiments in the available proven “off-the-shelf” irradiation test device
2. use the first experiment as a “scoping test” on standard fuel products (fuel and clad) to commission the test device, to master the experimental protocol and to confirm that the results fit with model predictions.

The first phase of the project implies to use on-line proven instrumentation and compatible with the device (place, feedthroughs...). It is acknowledged that the available instrumentation may not be sufficient to address all the scientific objectives described in section 2.1. To achieve the objectives of Task 2 of the project, innovative instrumentation, or adaptation of available sensors, will therefore be developed in parallel.

To maximise the measured parameters values during the test (internal pressure, clad deformation...), the test rods should be preferably selected in the high burn-up range (to enhance fission gas effects), e.g. in the range 40-65 GWd.t<sub>u</sub><sup>-1</sup>. However, the burn-up (BU) value is open and can be adapted depending on available candidates and participants’ proposals.

### 4.2 Test matrix proposal

The grid matrix will be progressively built based on fuel rod samples proposed by participants. The proposed test matrix of Task 1 is the following:

Task	P2M Test #	Type of fuel	Type of cladding	Targeted volume fraction of melted fuel at maximum T plane	Comments
Task 1	1	Standard UO <sub>2</sub> BU # 50 GWd/t <sub>u</sub>	M5 / Zirlo	5%	Calibration of the experimental protocol
	2	Standard UO <sub>2</sub> BU # 50 GWd/t <sub>u</sub>	M5 / Zirlo	10-15%	Same fuel as #1 (from an adjacent stack) Go / No Go for Task 2

The present proposal concerns only Task 1 and the financial quotation will be established for the two first tests. Tests of Task 2 are proposed in section 5.2.

Other types of fuel products could be tested afterwards, such as ATF or innovative fuels ( $U_3Si_2$ , fuel with high thermal conductivity...), Cr-coated Zy based claddings, modern Zy-based claddings, SiC claddings, etc...

If possible, the documented pedigree of the selected test segments will be made available to the project to complement the full pre-test characterisation.

### **4.3 Experimental rod refabrication and instrumentation**

In order to monitor on-line the kinetics of the evolution of the parameters of interest during the test, the refabricated rod (refabrication process is detailed in reference [4]) will be equipped with sensors enabling on-line evolutions of; i) the rod internal gas pressure (RIP) and/or the gas composition (see reference [5]); and ii) the fuel centreline temperature.

Other qualified sensors might be implemented if available. In particular, on-line clad outer diameter measurement is of prime interest and shall be implemented as early as possible in the test device and therefore in the test matrix.

Independently from the above technological integration issues, the selection and the specification of the sensors (measurement range, resolution...) will strongly depend on the test design and the models used to define the test protocol (see below).

## **5. EXPERIMENTAL IRRADIATION DEVICE AND EXPERIMENTAL PROTOCOL**

### **5.1 Overview of the project**

The overall transient that the project wants to explore is schematised in Figure 2 below. It also indicates the main physical phenomena affecting the fuel or the fuel-clad gap and impacting potentially the clad deformation

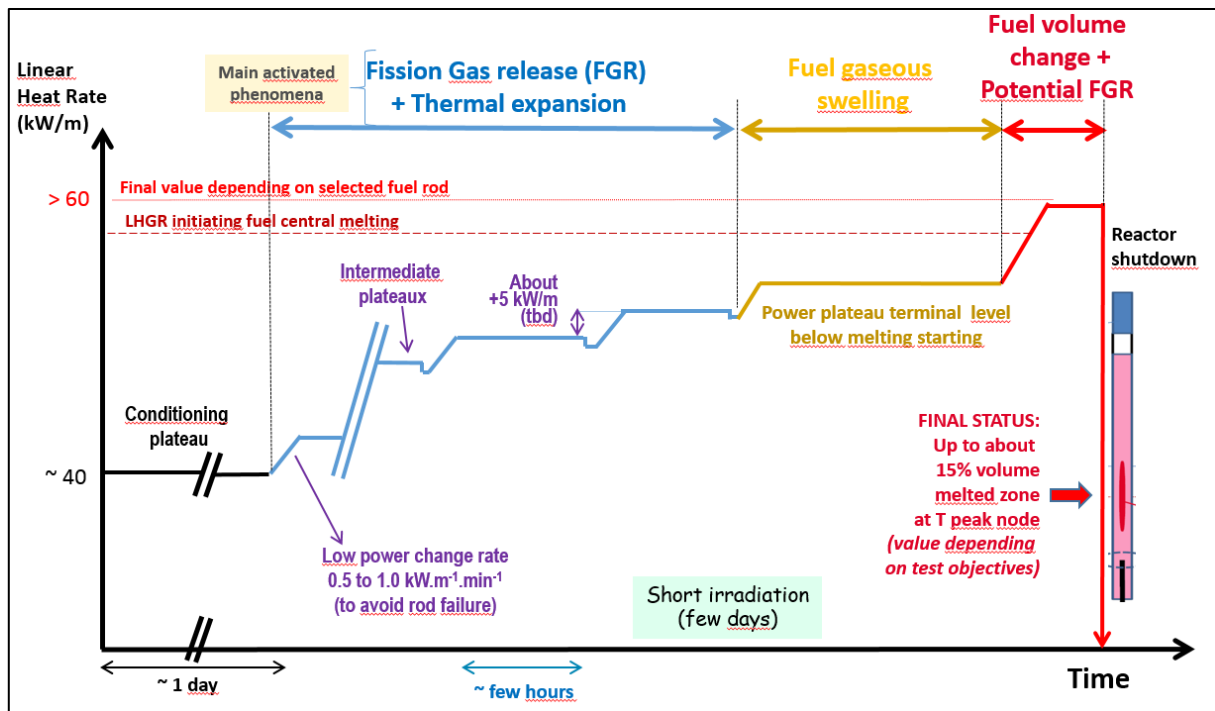


Fig. 2: Schematic of the envelope configuration of the slow transient that the project wants to investigate

To implement an in-pile test in a timely manner, a two phase approach has been proposed. The first one will address the “fuel melting issues” and the second one the “fuel swelling issues”. “Melting” will be investigated first because devices are operational, whereas the in situ cladding deformation measurement required for the “swelling” phase is still under development.

### 5.1.a Task 1 implementation

The main objective is to reach high LHGR values (up to  $> 60 \text{ kW.m}^{-1}$ ) on high burn-up fuels. This requests high neutron flux environment.

The proven Pressurized Water capsule (PWC) in BR2 reactor (SCK•CEN, Mol, Belgium) is well suited for power to melt transients (see Figure 3). The LHGR of a high burn-up test rod will be increased stepwise until the incipient fuel-melting threshold and then the targeted melted volume fraction are reached (see Figure 2 and reference [6]).

The test device allows internal pressure measurements (or rod axial extension measurements, alternatively). The temperature in the centre of the bottom of the fuel stack is also measured.

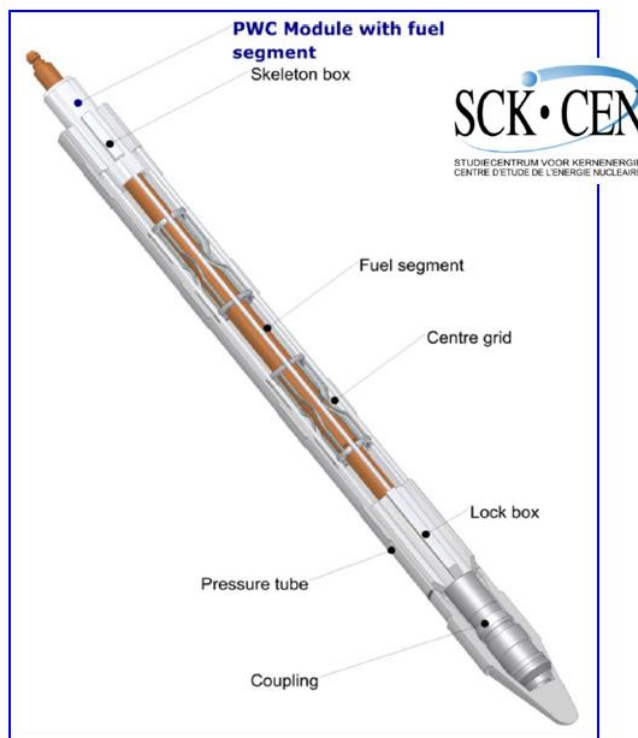


Fig. 3: Schematic of the PWC capsule to be used in BR2

### 5.1.b Experimental protocol proposal for Task 1

Figure 4 below represents the experimental protocol proposed for Task 1. The test itself is anticipated to last two days, but the process in BR2 will last one week, including test preparation and post-test handling. It is possible to run a direct power-to-melt ramp test, which would be a few minutes shorter (see reference [8], p. 187), but it would not fit with the overall objective of the project which is to investigate the behaviour of fuel rods during a **slow** transient. Therefore, it was chosen to reproduce a whole slow transient terminated with a power-to-melt transient.

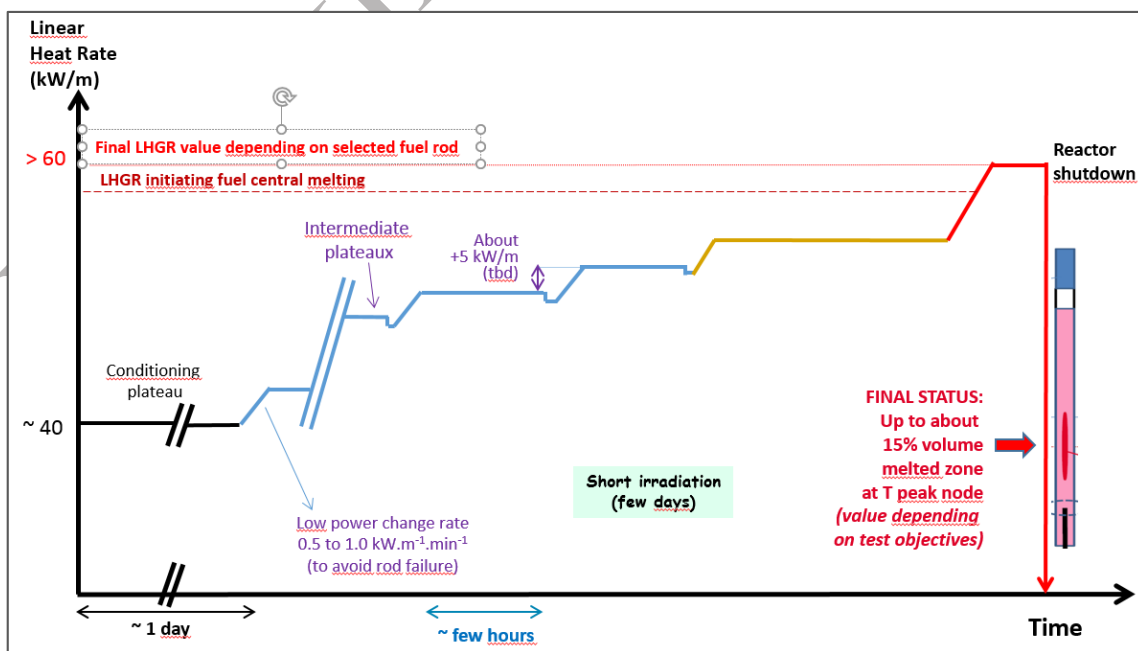


Fig. 4: Experimental protocol proposed for Task 1 in BR2

To improve the RIP measurement, it is proposed to perform small “power dips” at the end of each LHGR plateau, in order to slightly reopen the gap and to favour the axial gas transfer to the plenum where the pressure transducer is located. However, the magnitude of the dip should be small enough not to change the cracks pattern of the fuel pellet resulting in additional delayed gas releases (that could interfere with the gas already released in the free volume during the power plateau).

### 5.1.c Detection of fuel melting and expected final rod status

The terminal plateau at very high power level should initiate a “lens” of molten fuel at the peak power node. More precisely, the target is to obtain a melted zone representing a volume fraction ranging from 5 to 15% in the two first tests at the hottest elevation of the test rod. The reactor power will then be shut down in such a way that the final status of the rod is preserved and rod failure during the power decrease is precluded. Destructive PIEs will be performed and should exhibit similar feature as those shown in Figure 5 below. It represents a crosscut of an experimental rod, which have experienced a power-to-melt test in another program.

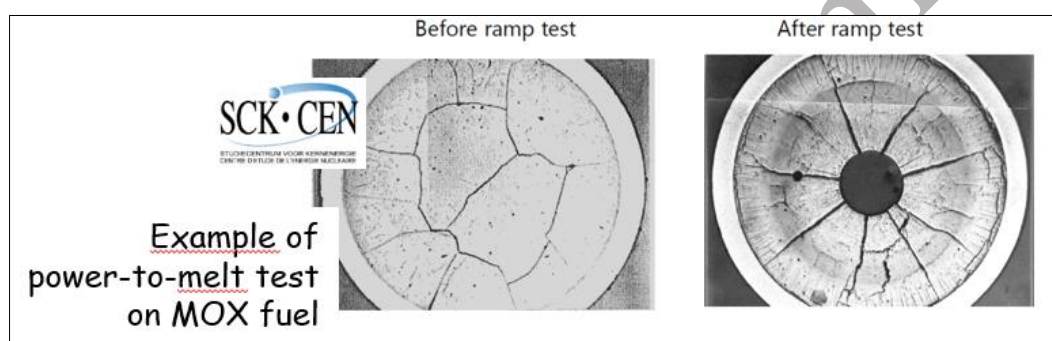


FIG. 5: Crosscut of an experimental rod after a test reaching the central melting

Figure 6 represents schematically the axial cross cut after a power-to-melt experiment. The axial extension of the melted zone will be mastered using the measured in-reactor axial neutron flux profile and the calculated “power to melt” based on models validated on former experiments. It is a challenging issue, but feasible thanks to the previous experience feedback.

To improve the monitoring of the fuel melting approach, it is suggested to shift slightly the test rod to put the centreline thermocouple (TC) closer to the peak power node. However, it is not certain that the TC will detect the incipient melting, because the heat transfer linked to the fuel phase change will be preferentially exchanged on a radial way (a specific study shall be made to optimise this measurement). Figure 7 represents an example of BR2 power axial profile, to better illustrate this suggestion.

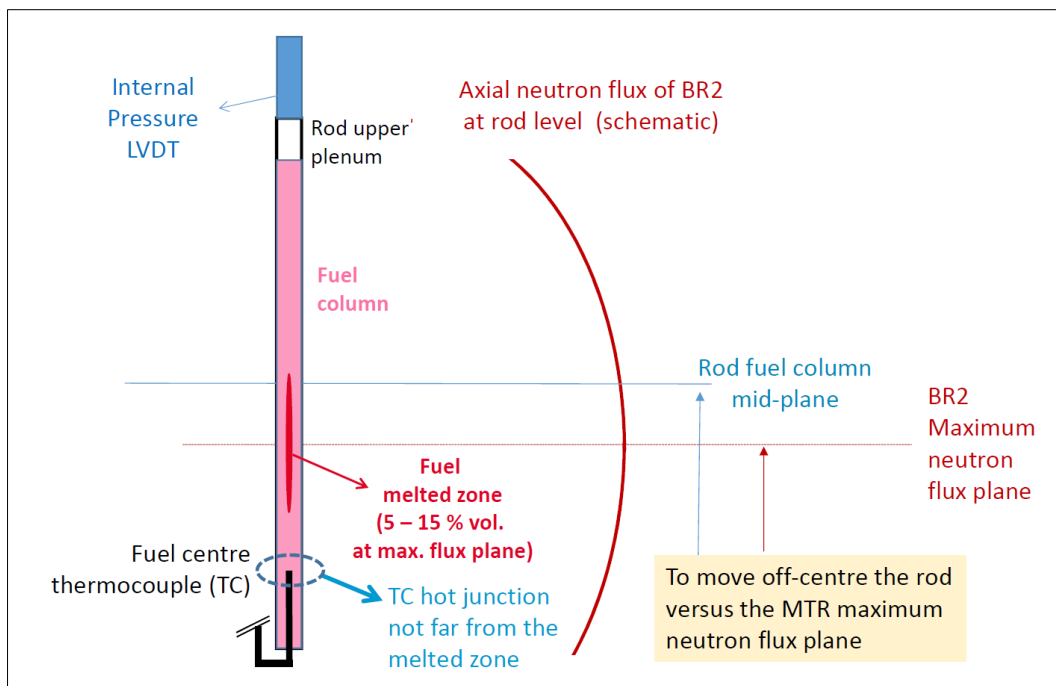


Fig. 6: Schematic of the axial cut of the rod after a successful test (fissile stack length is about 50 cm)

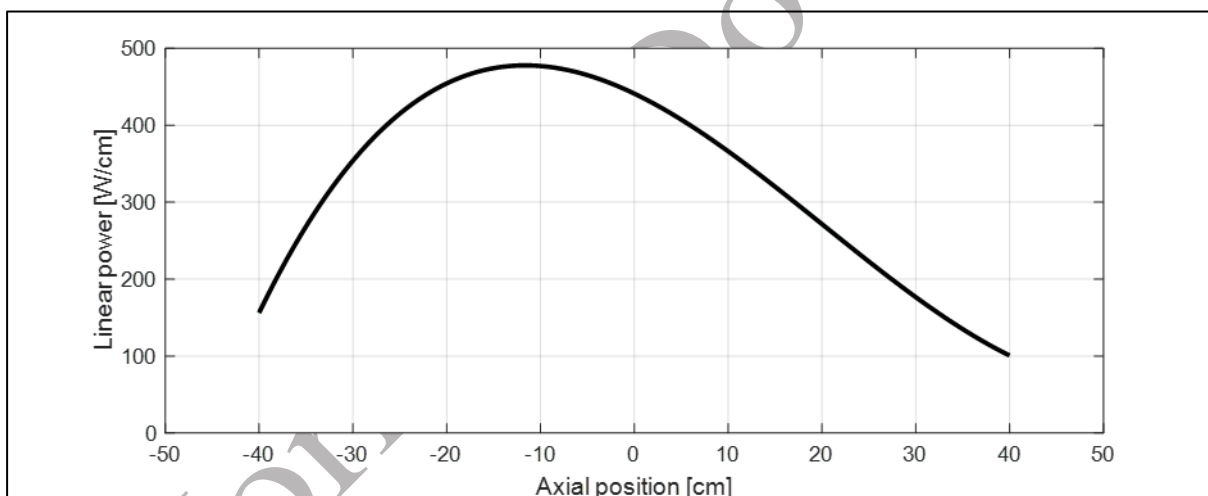


Fig. 7: Example of axial power profile in the BR2 reactor

Mechanisms impacting clad loading are illustrated in Figure 8 below, including the incipient melting effect.

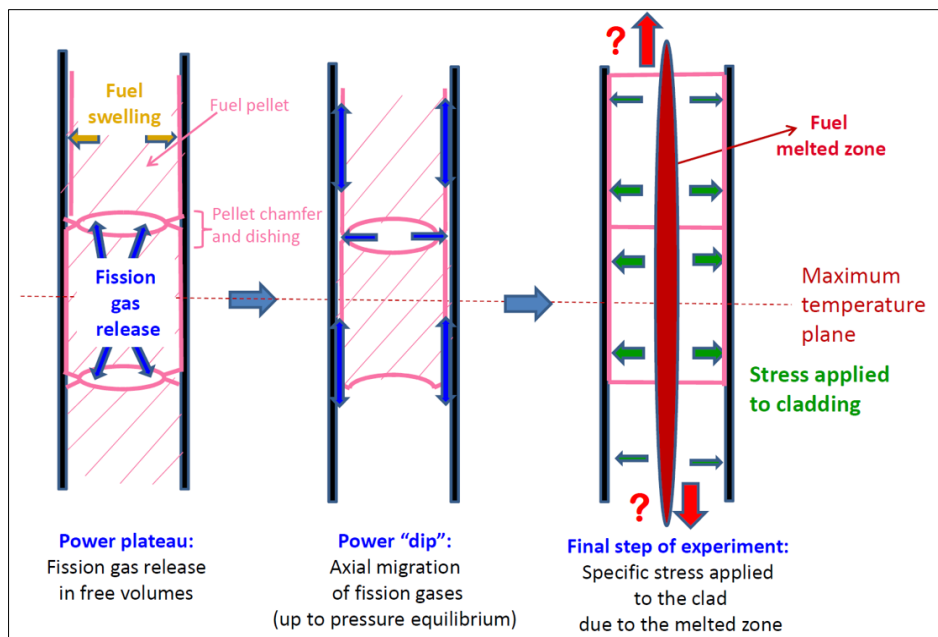


Fig. 8: Illustration of mechanisms provoking clad loading, and specific effect of incipient fuel melting

#### 5.1.d Post irradiation examinations

Hot cell laboratories used for implementing tests #1 and #2 of Task1 will be the LECA at CEA Cadarache and the LHMA at SCK•CEN Mol.

→ **Non-destructive post-irradiation examinations (NDEs)** for both tests will implement the following techniques (location to implement them can be slightly adapted depending on the final status of the rod after the test):

Phase	Cadarache	Mol
Before refabrication (father stack)	Axial profilometry Gamma scanning	
After refabrication	Welding checking Electrical test of TC and LVDT	
Transportation		
Before test		Rod tightness Visual inspection Electrical test of TC and LVDT
After test		Visual inspection Gamma scanning (LHMA)
Back transportation		
After test	Axial profilometry Clad health by Eddy Current Rod puncturing and measurement of the internal free volume	

→ **Destructive post-irradiation examinations (DEs)** will be performed after rod puncturing. The proposed programme consists of examining three metallographic cuts by microanalysis:

- one longitudinal cut, near the maximum temperature plane.

- one radial cut, also near the maximum temperature plane, for progressive polishing.
- one radial cut in a reference zone (e.g. extremity of the rod) or in another zone presenting a specific interest.

On each cut, metallographies will be implemented before and after chemical etching, for:

- measuring the spectrum of fuel grain sizes versus the pellet radius
- taking micrographies at different radii
- studying the pellet-cladding interface.

Then microanalyses with Electron Probe Micro-Analysis (EPMA) and Secondary Ion Mass Spectrometry (SIMS) will be performed in a coupled way to:

- set up a quantitative balance for the xenon distribution, to be compared to building codes
- identify distribution and chemical forms of some fission products of interest, by co-localisation: I, Cs, Te, Nd, Mo, Ru (for covering the various volatility classes) and even Pu.

Two other microanalysis techniques will be also carried out:

- micro-beam X-Ray diffraction at various radius values
- Electron Back-Scattered Diffraction (EBSD) to know the microstructure and the orientations at the fuel grain level, and at different radii.

### *5.1.e Main experimental steps*

Starting from a LWR father rod (available off-the-shelf at the hot cell LECA at CEA Cadarache), the experimental process for Task 1 is as follows:

- extraction of two adjacent segments from the father irradiated fuel rod
- rRefabrication in Hot Laboratory of two twin fuel pins, with characterisations
- transfer of the both pins to SCK•CEN
- pre-test checking and first test in BR2
- NDEs at SCK•CEN and experts meeting to evaluate results and decide conditions of test #2
- DEs at CEA (planning not impacting the test #2 preparation)
- pre-test checking and second test in BR2
- NDEs of test #2 at SCK•CEN
- DEs at CEA.

## **5.2 Task 2**

Task 2 of the project aims to study the cladding deformation induced by fuel solid and gaseous swelling during a slow transient. To achieve this goal, specific development or adaptation of the test device are requested, favouring the use of a rig with multiple on-line instrumentation. In particular a reliable and accurate **on-line clad outer diameter sensor allowing axial scans**, has to be implemented.

It is recommended to benefit from the Institute For Energy's (IFE) (Halden, NO) experience feedback in this matter. Options including PWR loop or capsule in an MTR at RIAR, ROSATOM; or dedicated loop or capsule in an ATR at INL (DOE, USA); or a new capsule in BR2 should be investigated.

It must be understood that Task 2 is less well-defined than Task 1 as it requires further developments. Therefore the proposed test matrix and test protocol below are preliminary.

Nevertheless, they may help potential P2M participants to figure out the kind of result they will eventually get. Technical details will be refined after the test reactor for Task 2 is selected.

Tentative test matrix for Task 2 is the following:

Task#	P2M Test #	Type of fuel	Type of cladding	Targeted volume fraction of melted fuel at maximum T plane	Comments
Task 2	3	Cr-doped $\text{UO}_2$	M5 / Zirlo	tbd	Final test conditions to be defined by participants
	4	Gd – doped $\text{UO}_2$	M5 / Zirlo	tbd	Final test conditions to be defined by participants
	5	Gd or x – doped $\text{UO}_2$	E110 or equivalent.	tbd	Final test conditions to be defined by participants. Comparison full pellet/hollow pellet

From test #3, it will be also possible to define more options (e.g. grain size, type of neutron absorber...).

A possible experimental protocol is represented in Figure 9. This test protocol will be discussed among the participants after Task 1 results.

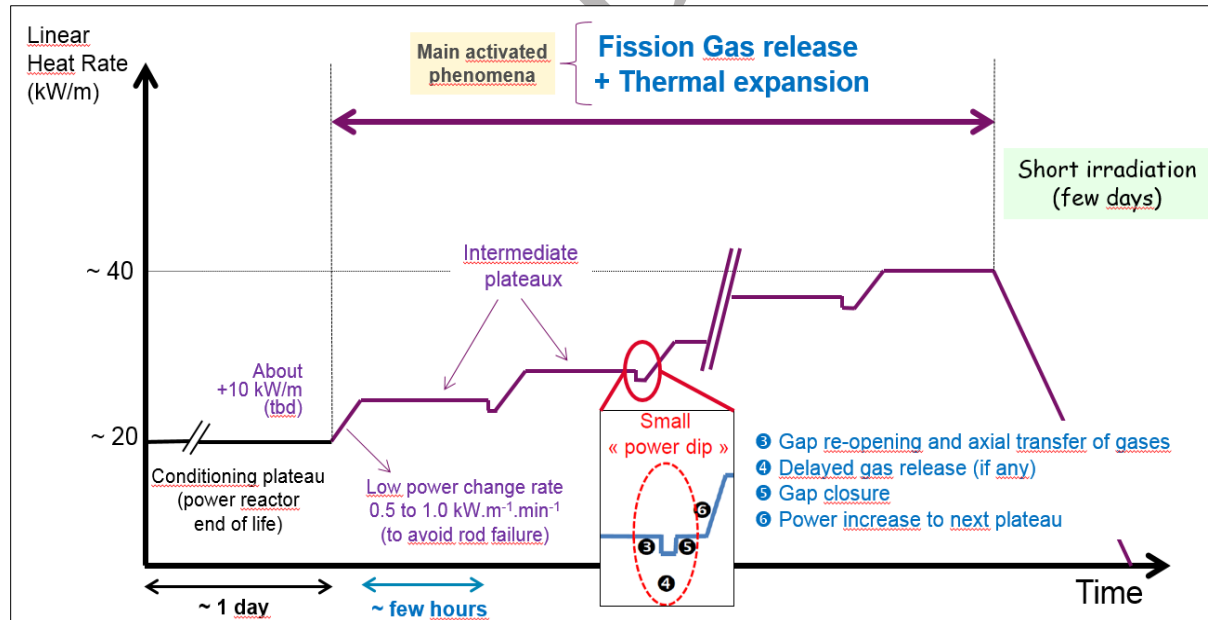


Fig. 9: Experimental protocol proposed for Task 2 (with clad outer diameter measurement)

## 6. BRIEF REVIEW OF THE STATE-OF-THE-ART

This review is given in **Annex 1** of this document.

## 7. FUNDING LOGIC AND TENTATIVE PLANNING

The cost endorsed by the three partners of the core group is:

- **50 % of the total cost of test #1 of Task 1 (qualification of the experimental protocol)**
- **30 % of the total cost of test #2 of the Task 1 (first experimental test)**
- **30 % of the total cost of the tests planned in Task 2 (other experimental tests).**

The other partners gathered through an NEA joint project will pay the remainder: 50 % for Task 1, test #1, and then 70% for the subsequent tests. Individual contribution will be based on the current contribution calculation mode proposed by the NEA.

Tentative planning is as follows:

- February 2019: Dedicated meeting organised by OECD/NEA
- May 2019: Finalisation of the P2M Joint Programme description,
- Fall 2019: Reception of all partners signatures and kick-off meeting
- January 2020: Preparation of refabrication for both rods of Task 1 at CEA Cadarache
- June 2020: Checking of two rods after refabrication
- July 2020: Transportation of both rods to BR2
- Fall 2020 : Test #1 in PWC capsule in BR2
- Spring 2021: NDE examinations on tested rod #1 and transport back to CEA Cadarache
- June 2021: Follow-up meeting and finalisation of test #2 conditions
- Fall 2021: Test #2 in PWC capsule in BR2
- Spring 2022: NDE examinations on tested rod #2 and transport back to CEA Cadarache
- Mid 2023: End of the Task 1
- Mid 2023: Test #3 (Task 2) if decided



## REFERENCES

- [1] BIGNAN G., “The Jules Horowitz Reactor: A new high performance European MTR with modern experimental capacities – Toward an international user Facility”, 16<sup>th</sup> IGORR Conf., 17-21 November 2014, Bariloche (AR).
- [2] BRAVO X., et al., “The Jules Horowitz Reactor: Preparation of the commissioning phase and normal operation”, RRFM 2017 Conf., 14-18 May 2017, Rotterdam (NL).
- [3] GONNIER C., et al., “Preparing JHR international Community through the developments of the first experimental capacity”, 17<sup>th</sup> IGORR – RRFM 2016 Conf., 13-17 March 2016, Berlin (D)
- [4] BERDOULA F., et al., “Fuel rod instrumentation techniques implemented in LECA facility – Development of advanced instrumentation techniques”, IGORR 2009 Conf., 27-30 October 2009, Beijing (CN)
- [5] ROSENKRANTZ E., et al., “An Innovative Acoustic Sensor for In-Pile Fission Gas Composition Measurements”, IEEE Transactions on Nuclear Science, 2013
- [6] VAN DYCK S., et al., “Experimental irradiations of materials and fuels in the BR2 reactor”, IAEA Tech. Meeting on commercial products and services of research reactors, 28 June – 2 July 2010, Vienna (AT)
- [7] NEA/WGFS “Nuclear Fuel Safety Criteria Technical Review”, 2012, second edition available at [www.oecd-nea.org/nsd/reports/2012/nea7072-fuel-safety-criteria.pdf](http://www.oecd-nea.org/nsd/reports/2012/nea7072-fuel-safety-criteria.pdf)
- [8] SANNEN L., BODART S., GYS A., VAN DER MEER K., VERWERFT M., “Nuclear fuel rod qualification by ramp testing and pre- and post-irradiation examination”, Research Facilities for the Future of Nuclear Energy – Proceedings of an ENS Class 1 Topical Meeting, 1996, Edited by Hamid Aït Abderrahim, World Scientific, p. 187
- [9] MACDONALD P. E. et al., Response of unirradiated and irradiated PWR fuel rods tested under power-cooling mismatch conditions, Nuclear Safety, Vol. 19, N° 4, July-August 1978, p. 440
- [10] PIE report on six UO<sub>2</sub> fuel rods irradiated in IFA-677 high initial rating test, HWR-968

## ANNEX 1

### Examples of experiments at high linear power with/without final fuel incipient melting

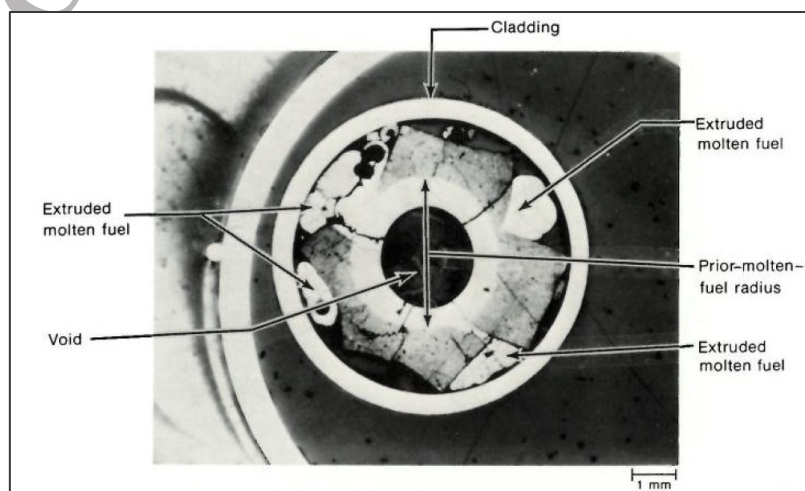
#### EXAMPLES FROM THE STATE-OF-THE ART

##### 1. Programmes conducted in the Power Burst Facility (PBF reactor, DOE, USA)

Unirradiated and irradiated PWR experimental fuel rods (Zr clad and  $\text{UO}_2$  with enrichment ranging from 9.5 and 20 wt%) have been tested in “power cooling mismatch” (PCM) conditions. These conditions corresponded to the formation of a stable film boiling maintained from 30 seconds to 11 minutes, at local linear power levels ranging from 45 to 80 kW/m. Irradiated rods (coming from Saxton reactor, burn-up values are indicated for only two rods: 17 and 16 GWd/t) were instrumented with internal pressure and clad elongation detectors. For unirradiated rods equipped with the same detectors, the fuel temperature is measured in the centre. Initial inner pressurisation was low (less than 40 bars at room T). Rods were tested singly or four at a time (in this configuration each rod had its own coolant flow shroud). Thirteen tests were performed in a first phase in the 1970s, on 21 unirradiated fuel rod (“PCM tests”) and on 9 pre-irradiated rods (“IE tests”).

Various final configurations for the tested rod have been obtained (see reference [9] for details). Some of them were not of interest, due to instrumentation malfunction or unexpected rod behaviour (too early failure, rod bowing, rod broke during cooldown...). However, depending on final clad surface and fuel central temperatures, strong evolution of the fuel pellets were observed in some cases. In particular, a fuel melting extending as much as 80% of the pellet radius has been obtained. Generally the molten fuel was contained at the centre of the fuel pellets. In isolated circumstances, molten fuel has been extruded from the pellet centre to the cladding. No significant molten fuel – cladding interaction was observed. Figure 1 below illustrates an example of a large molten zone.

A specific study was done on fission gases impact, either on fuel swelling or after their release. Among other results, they appeared as trapped in the molten fuel region and not released from the molten fuel to the rod plenum during the film boiling operation. These trapped gases apparently pressurised the molten fuel zone and caused a limited fuel rod swelling and some relocation of molten fuel. However, their effects produced no significant adverse behaviour in the tested rods.



*Fig. 1: Example of molten fuel extrusion above the film boiling zone of an pre-irradiated fuel rod:  
Rod IE-106, Test IE-3*

Compared to the P2M proposal, the film boiling conditions corresponded to very high clad temperatures (indicated values ranged from 900K to 1850K), and therefore a very different radial temperature gradient. Moreover, as the indicated burn-ups in reference [9] are low, the effect of the quantity of available fission gases is probably limited.

## **2. Test xM3 in the R2 MTR (Studsvik)**

This test concerned an experimental fuel rod segment of PWR geometry, with UO<sub>2</sub> fuel and Zirlo cladding. Reached burn-up was 27 GWd/t. After refabrication, only a qualitative measurement of clad elongation was implanted on the rig.

Tests started with an 18 hour long conditioning plateau at 20 kW/m. It was followed by a staircase-type ramp protocol. Steps amplitude was 5 kW/m and each plateau lasted 1 hour. The rod did not fail at 70 kW/m. Expensive PIEs have been performed, showing that the central melting of the fuel was reached. However, these results are not public.

Compared to P2M, the burn-up was low and no on-line instrumentation for monitoring the parameters inside the rod (temperature and pressure) was implemented. Moreover, no pre-test / post-test comparison was made through the PIEs. This test was not supported by code analysis or benchmarking.

## **3. Power-to-melt tests in the BR2 MTR (Mol)**

Different tests have been implemented in BR2, targeting the incipient fuel melting. Figure 5 in the main text shows a crosscut of a high burn-up MOX fuel rod after such a test. Results are not public.

## **4. Halden Reactor Program (HRP): IFA-677 test at high initial linear heat rate**

This experiment concerned irradiation of six rods (four standard UO<sub>2</sub> and two doped {Al<sub>2</sub>O<sub>3</sub> – Cr<sub>2</sub>O<sub>3</sub>} UO<sub>2</sub> fuel rods), equipped with on-line instrumentation for internal gas pressure, fuel central temperature and fuel/cladding elongation. History of irradiation started in 2005 with a long plateau at high linear power (2000 hours at about 45 kW/m), for activating fuel swelling and fission gas release (see reference [10] for details). So objectives are more fitting with Task 2 of P2M.

However, some fuel rods were fresh, and the mean burn-up of others was about 26 GWd/t. The quantity of available fission gases was then too low to activate significant fuel swelling and clad deformation, but it will be an interesting comparison point for assessing the first plateaux of P2M.

## **5. Standard power ramp tests on LWR experimental fuel rods**

Many tests have been implemented in various MTRs (R2, OSIRIS, HBWR, HFR, MIR...), but rod characteristics, irradiation conditions, and therefore the objectives, were very different from the P2M ones:

- the experimental rod was the most often poorly instrumented
- the final LHGR values explored the technological failure limit and not above (e.g. 42-50 kW/m)
- the tested rods had a burn-up corresponding to the most critical zone for Pellet-Cladding Interaction (PCI) phenomenon: 25-40 GWd/t
- no central melting of fuel material was intentionally targeted.

## 6. Irradiation of fast reactor fuel pins at Beginning-of-Life (BOL)

Even if irradiation conditions and fuel products are different from LWRs ones (but not radically different versus the P2M targeted final conditions), one can mention the potential interest of some tests implemented on fast reactor fresh fuel pins (mainly for Sodium Fast Reactors power system (SFR)). Fuel central temperature is very high (e.g. more than 2400K) and not far from the incipient fuel melting during the first tens of hours of irradiation. The fuel microstructure evolves quickly and dramatically, forming, for example, a central hole without the step of melting. This hole is surrounded by typical “columnar grains” formed by a vaporisation / condensation mechanism for heavy nuclei. One example of pellet crosscut is given in Figure 2 below.

Such evolution could be found at the rod extremities for P2M and could constitute interesting comparison results.

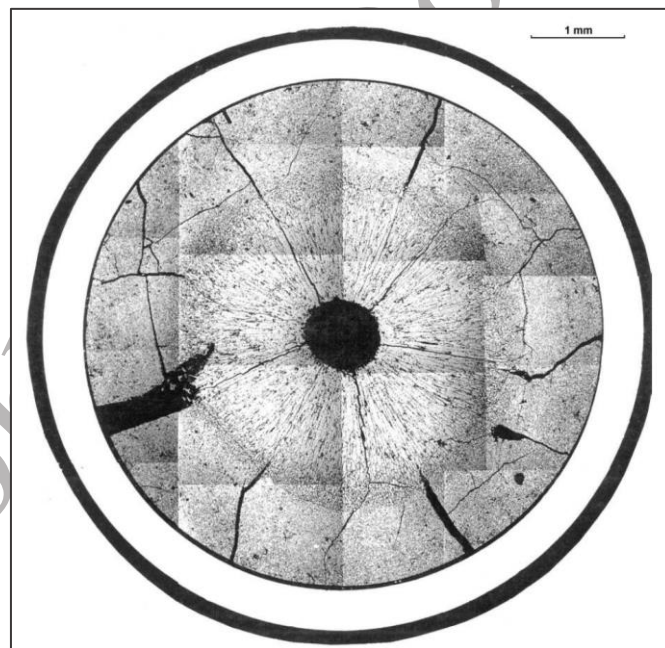


FIG. 2: Crosscut of a SFR PHENIX fuel pin after 60 days of irradiation at 35 kW/m