# Tests and Research Reactor Capabilities for Nuclear Fuel and Material Studies

**Background Paper for the Workshop "Building Multinational Fuel and Materials Testing Capacities for Science, Safety and Industry"**
**4-5 October 2018**

## 1. Introduction

The Nuclear Energy Agency (NEA) is pursuing an agenda to enhance innovations in the nuclear arena to move new technologies to application more rapidly. In this context, the Nuclear Science Committee (NSC) has launched an initiative to strengthen experimental capabilities to test evolutionary and innovative nuclear fuels and materials. As part of this initiative, the NSC held an international workshop on "Enhancing Experimental Support for Advancements in Nuclear Fuels and Materials" in January 2018, which brought together participants representing utilities, fuel vendors, technical support organisations (TSOs), regulatory bodies, research organisations and experimentalists. The dialogue focused on identifying requirements and barriers that each participant faces when deploying innovative materials. A brief summary of the discussions held during the four sessions with speakers representing industry, safety, research institutions and experimental facilities is available in Appendix 1. A workshop agenda and list of workshop participants can be found in Appendices 2 and 3 respectively. It was agreed that additional alignment on the use of material test reactors, as well as, international frameworks facilitating transport and disposal of nuclear materials would allow for enhanced collaboration between participants. Furthermore, the decrease in available infrastructure was noted; participants emphasised the importance of material test reactors to ensure sufficient testing of advanced fuels and materials. It was agreed that multi-lateral and multi-national co-ordination of experimental programmes would be beneficial in order to best utilise existing infrastructure and to clearly identify gaps that can be best filled by restarted and new facilities.

After the workshop, there were some efforts to help prolong the operation of the Halden reactor. Nevertheless, in June, its shutdown became official, drastically changing the available experimental landscape. As a result, there are now concerted efforts being undertaken in several member countries to mitigate the consequences of the Halden reactor shutdown. Under these circumstances, the conclusions of January's workshop became yet more relevant and their urgent implementation is necessary.

This background document is an aide to facilitate such outcomes. At a high level, it summarises the types of experimental capabilities presently available, contrasted against the capacity recently relinquished as a result of the Halden shutdown. Furthermore, it is a preliminary attempt to identify several existing facilities that could potential play a major role in addressing high priority fuel and materials testing needs.

The workshop on "Building Multinational Fuel and Materials Testing Capacities for Science, Safety and Industry", on 4-5 October 2018, will continue to advance this dialogue as the following objectives are pursued:

- highlight the strategic necessity for multinational fuel and material testing capacities to meet science, safety and industry needs;
- move further towards establishing an international framework of key infrastructure sites (RRs and other facilities) via the mechanism of NEA Joint Projects, in order to provide state-of-the-art experimental evidence for qualification and validation purposes;
- discuss proposals for potential joint projects.

Input on experimental infrastructure gathered from the workshop will be important to refine the contents and conclusions of this document. Its revision and finalisation will therefore be carried out during the workshop and in accordance with its results.

## 2. Summary note

The closure of the Halden reactor has created a vacuum in the nuclear fuel and material research world. In order to maintain a minimum level of continuity, at least to address the most important issues, initiatives need to be taken at the international level to favour the use of selected research reactors (RR) for joint programmes. It is believed that such joint programmes will also create the basis for bilateral programmes, as needed by the industry and safety bodies.

The main problem when addressing the above is that Halden was doing almost everything; partly because of its own capabilities and partly because many other research reactors have been closed over the course of the last two to three decades. Test technologies were transferred from some of these closed reactors to Halden, which enhanced the Halden reactor's role as the global test station. The main factors that made this possible are presented in Section 5. This also means that the few RRs still operating remained at – or gradually drifted towards – the periphery of nuclear fuel research, and there are not many left where new programmes can be established, at least in the time frame of the next five to six years.

On the other hand, there is other infrastructure – besides RRs – offering research and development possibilities. This basically consists of power reactors, where irradiations at normal conditions can be efficiently carried out and hot cells, where fuel examinations and some degree of testing can conducted. In between, on-site fuel inspections are also a valuable source of fuel behaviour data and information. The interplay between these types of infrastructures is described in Section 3.

An outline of the technical items of interest in nuclear fuel and material research is set out in Tables 1 and 2. Considering the relative importance of the different items and the fact that some of the items may not require research reactors, items 4, 6 and 7 in Table 1 have been selected as those of the highest priority for tests requiring RRs.

*It is expected that the workshop will provide recommendations regarding where the high priority tests – loss-of-coolant accident (LOCA) experiments, the reactivity initiated accident (RIA) and the power ramps experiments – could be performed in the future. First considerations to be examined are below:*

- *For loss-of-coolant accident (LOCA) testing, one or two in-reactor tests per year may be needed based on experience. The NEA may negotiate with Studsvik to widen their NEA Studsvik Cladding Integrity Project (SCIP), to include a few reference tests run in a test reactor to be designated, at conditions to be defined.*

*SCIP LOCA tests are currently done in a hot cell furnace (external heating). Hot cell vs. reactor data would enable the assessment of the effect of external vs. internal heating on fuel fragmentation, if any. Beyond these phenomenological investigations, LOCA related licensing tests will be required to qualify the new types of fuel concepts under development. Lead Test Fuel Rods of these Accident Tolerant Fuels (ATFs) will be irradiated as early as 2019 in a few Nuclear Power Plants and will be available for LOCA tests five to seven years later. MIR, Cabri or Lorelei LOCA Loop in Jules Horowitz Reactor (JHR) are to be considered for possible LOCA tests in the future.*

- *For reactivity initiated accident (RIA) testing, experience shows that two to four tests per year can be expected. The Cabri reactor and possibly also the Transient Reactor Test Facility (TREAT) reactor can be used in the future. An OECD/NEA programme was established in the past based on Cabri. Such programme can be extended, e.g. to address more modern alloys, as the current RIA database is mainly based on old cladding. In fact, 90% of the data were produced more than 20 years ago and only 9 data points in total pertain to Zirlo and M5, i.e. to the alloys currently used in most of French and US pressurised water reactors (PWR).*
- *For power ramps and other operational limits, an overall number of five to ten tests per year can be expected, based on Halden experience. For this category, the situation is more complex in that there are not readily available test reactor facilities that can handle this type of fuel operation. As for the Jules Horowitz Reactor (JHR), the time until the start of operation may be too long to comply with the industry's needs in the next five to six years. Test reactors such as the Belgian Reactor 2 (BR2), MIR and ATR could, in principle, handle these tests. However, in some cases this would require the installation of suitable equipment and a framework to fix issues such as cost, timeframe, licencing and residual reactor operational time. As a first step to evaluate credible options, the NEA may start a short-term dialogue with these reactors and a few other selected research reactors to assess capabilities and willingness to address this type of tests. In parallel, discussions with selected industry bodies (e.g. vendors and utilities) can be used to assess actual needs on the short and medium term, and how NEA can support such needs.*

Regarding all other items in Tables 1 and 2, they are considered as less urgent or as having solutions that do not necessarily require test reactors. On a general basis, it would be useful to have an overview of the power reactors where experience and interest exist for base irradiations of fuel to be subsequently handled for Post Irradiation Examination (PIE) and/or further RR testing.

It would also help to have an overview of power reactors and research reactors where experience is readily available for base irradiations of unfuelled cladding material, or of reactor materials to be subsequently used for PIE or post-irradiation testing (in-pile and out-of-pile).

**Table 1. Fuel performance studies foreseen in the future and related facilities**

Note: The items in shaded areas are those of higher priority for testing in RRs

| | Items | Ways to address them |
|---|---|---|
| **1.** | Fuel performance[(1)] at normal operating conditions for advanced fuel, modified cladding, additive fuel, burnable poison, MOX, high burn-up, without instrumentation for on-line monitoring of fuel performance | When irradiation can be performed at normal operating conditions (normal cooling, water chemistry, power level, burn-up), and when the irradiation satisfies the criteria set by the licencing authority in the relevant country, the assessment can be carried out through nuclear power plant (NPP) irradiations. Alternatively, RR tests may be required. Interim inspections with non-destructive (ND) testing can be carried out during outages, including growth and corrosion in outer rods in the assembly. Full PIE, ND and destructive examinations, can be done at end of irradiation. |
| **2.** | Behaviour of advanced/ exotic cladding materials such as for accident tolerant fuels (ATF) at normal light water reactor (LWR) coolant conditions | a) Can be done through unfuelled coupon irradiation in NPP, either at wet or dry conditions depending on purpose, followed by PIE.<br>b) Can be done through Lead Test Fuel Rods (LTFR) inserted in NPP cores. Fuelled rods are necessary when physical interactions between fuel pellets stack and cladding material is at stake (assessment of the gap closure kinetic, characterisation of the interface chemical bonding, etc.). Initial number of LTFRs should be such that enough experimental fuel rods are available for PIEs and experiments (i.e. after each cycle, depending on the parameters of interest: free irradiation growth, creep down, swelling, etc.).<br>c) Same as above, but with irradiation in an RR when more suitable than NPP, e.g. due to licensing or requirements for on-line detection of performance. |
| **3.** | Behaviour of standard or advanced fuel with on-line instrumentation and/or of cladding materials at non-standard water chemistry conditions | Irradiations with on-line fuel rod instrumentation can only be carried out in an RR. Qualifications of water chemistry effects on fuel cladding or reactor internals (as it occurred for hydrogen water chemistry in the past) also require an RR. Water chemistry studies may also consist of RR tests following a base irradiation in an NPP. |

**Table 1. Fuel performance studies foreseen in the future and related facilities (continued)**

| | | |
|---|---|---|
| **4.** | Operational limits, i.e. power ramps[(2)], load following, conditioning/ deconditioning, rod overpressure, dry-out/ post-dry-out , margin to fuel melting | These operational limits can only be assessed through RR testing, since they imply testing at conditions beyond the acceptable NPP operational range. These tests can be done to assess the margin for safe operation of current fuel, or to demonstrate the performance of advanced fuel. They may imply testing with fresh fuel, but it mainly involves pre-irradiated fuel, including (very) high burn-up. Normally, the pre-irradiation is carried out in NPPs (Cf 2.b), as in the case of almost all power ramps, because the irradiation power history and irradiation conditions (e.g. load following, irradiation temperature, thermo-mechanical state, coolant chemistry) should be as prototypical as possible. |
| **5.** | Fuel failure degradation | It can be done in RR only, using either un-irradiated or pre-irradiated fuel. |
| **6.** | LOCA tests, addressing e.g. fuel fragmentation | It can be done in RRs but also in hot cells. In principle, it does not require a pressurised in-pile loop. Normal low-temperature/pressure RR conditions may be adequate. It requires fuel rods irradiated in prototypical conditions (Cf 2.b) |
| **7.** | RIA testing, failure limit and mechanisms | RIA tests can only be done in specialised pulse reactors, such as the Cabri or TREAT reactors. Requires rod re-fabrication capabilities to prepare the fuel specimens and irradiated fuel candidates at the appropriate burn-up level and in prototypical conditions. |

(1) Needs for commercial water reactor fuel are addressed here. Other fuel needs are to be seen on a case-by-case basis.
(2) The subjects addressed in Item 4 are very important, especially power ramps. Power ramps are normally done with fuels that have varying burn-up and different cladding designs/conditions. Studsvik developed a technique to simulate power ramp with hot cell testing (mandrel tests with iodine addition). While this can be interesting for mechanism assessments, it cannot substitute power ramps as done in RRs.

**Table 2. Reactor material studies foreseen in the future**

| | Items | Ways to address them |
|---|---|---|
| **1.** | Reactor Pressure Vessel (RPV) ageing | Material irradiations can be done in NPPs and RRs. |
| **2.** | Internals ageing, stress corrosion cracking initiation, growth | Base irradiations can be done in NPPs and RRs. Various options for actual testing can be done in an NPP, or in a RR, or in a hot cell autoclave. |
| **3.** | Concrete ageing | Extrapolation to high doses can only be done in an RR. Testing at <100°C |

## 3. Overview of technical infrastructure

Nuclear test reactors were constructed in the post-world war period, mainly for the purpose of supporting potential nuclear energy developments in a number of countries. While most of these reactors were intended to sustain national goals, their utilisation tended to diminish with time, as nuclear power reached maturity at national and international levels. However, there remain important questions in the fuel and material area that will need to be answered – both at present and in the future due to:

- the implementation of more aggressive irradiation conditions in most of the commercial NPPs (longer fuel cycles, higher burn-ups, chemistry changes, intensive load following, etc);
- the evolution of the regulation (new safety related requirements);
- the evolution of modeling and simulation capabilities.

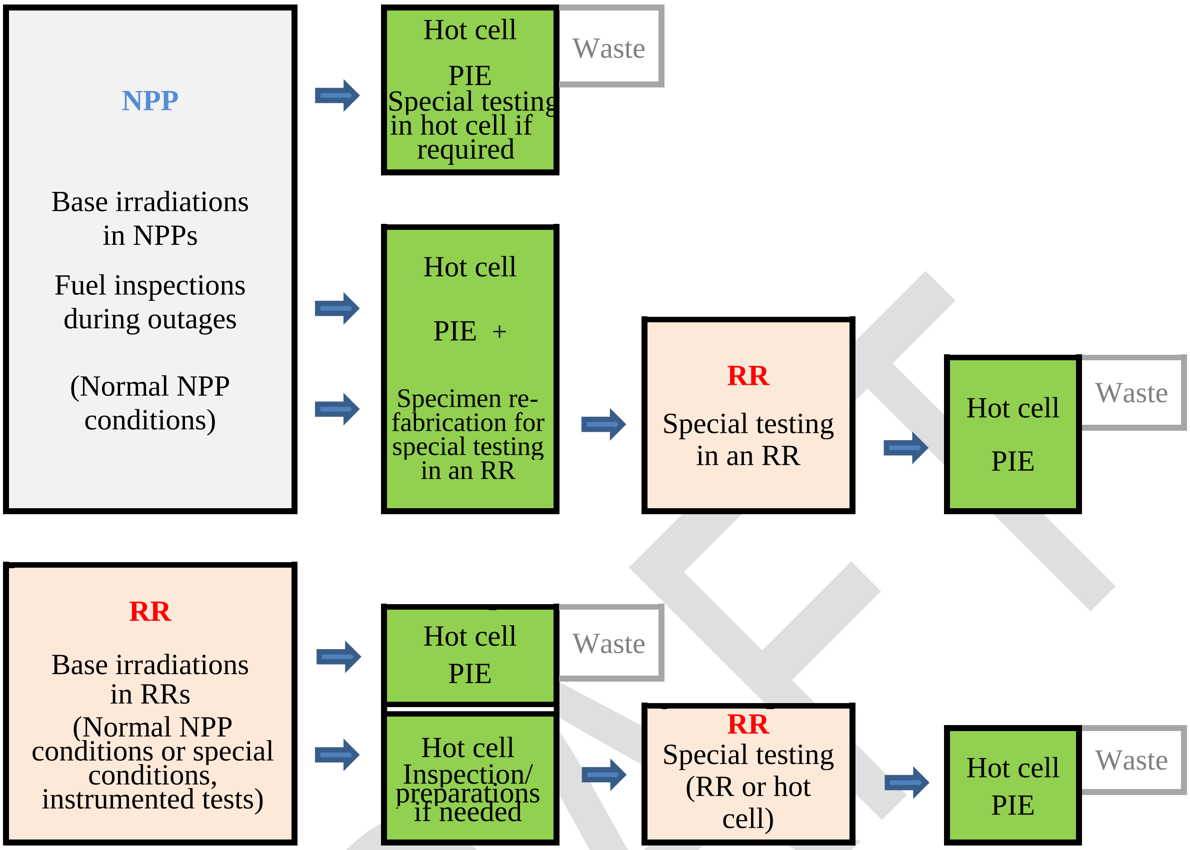
In order to address these evolving issues, a facility infrastructure that can sufficiently provide such answers would be necessary.

The infrastructure for nuclear fuel and material research consists mainly of:

- NPPs, where advances in fuel design can be addressed at normal operating conditions, either in normal fuel assemblies or in so-called lead test fuel rods/assemblies.
- RRs, mainly for irradiation at conditions not achievable in NPPs, such as special water chemistry, high neutron flux, high power and diminished cooling, irradiation conditions leading to fuel integrity limits/fuel degradation (safety margins assessment). Tests with instrumented fuel rods or material specimens are also done in RRs.
- Hot cells for post-irradiation examination and testing, as well as for the preparation of fuel/material specimens suitable for further testing in RRs.

Figure 1 provides an overview of how NPPs, RRs and hot cells usually interact with each other. Base irradiations are a key factor in that they provide the inventory of irradiated fuels/materials needed for further assessments – in hot cells or in RRs. Base irradiations are most efficient when done in power reactors, which should be preferred unless special irradiation conditions are required. RRs are a must for safety and operational limits assessments, as well as for special testing, e.g. at new water chemistry conditions or with on-line instrumentation.

**Figure 1. Main tools and steps in fuel and material testing**




## 4. Overview of international experience with research reactors

While RRs in countries such as the United States, Japan, France, Canada and the United Kingdom primarily served national goals, in other countries their utilisation was broadened to accommodate objectives at international level, through projects jointly financed by groups of foreign institutions and industry, as well as safety bodies. Examples of RRs where these types of projects were organised are the R2 in Sweden, the High Flux Reactor (HFR) in the Netherlands, the Danish Reactor 3 (DR3) in Denmark, the BR2 in Belgium, and most of all the Halden Boiling Water Reactor (HBWR) in Norway.

The R2 reactor in Sweden (50 MW) was primarily known for its ramp test capability and – internationally – for the multi-user programmes Over-Ramp, Super-Ramp, Inter-Ramp and Trans-Ramp, which consisted of a series of power ramp tests conducted on commercial LWR fuel types. The ROPE project was another R2-based international project which addressed the rod overpressure issue, i.e. the effects of rod internal pressure exceeding the system pressure. Such effects were studied using short rod specimens cut from commercial high burn-up fuel rods. The R2 produced valuable fuel data, but its operation was suddenly ended by the owner in 2005.

The HFR reactor (45 MW) in the Netherlands was also known for its important contributions in fuel performance assessments, notably in the area of power ramps, which were conducted mainly for the German industry but also in a broader international context. About a decade ago, the HFR ended its power ramp programmes and dismantled the ramp facility.

The BR2 reactor (58 MW) in Belgium conducted irradiation and testing of nuclear fuel and materials for a number of years, mainly in the European context. Among others, a loop facility called Callisto operating at PWR conditions was utilised for a number of years. This loop is not currently available or not being operated today. A new pressurised water (PWC) capsule is now available for rodlets irradiations up to 100-cm long. BR2 has been refurbished in 2016 and the Be matrix has been replaced enabling 20 years of operation with no major refurbishing expected. While the BR2 remains in principle available for irradiations in the fuel and material area, the actual fuel testing currently being carried out is very limited, if any. One should note that the BR2 has been used for JHR fuel testing in the past – a testing that may be resumed in the future. Such type of testing is done at RR conditions (i.e. at 50-60°C) and at atmospheric or low pressure (i.e. away from LWR conditions).

The Risø reactor in Denmark (DR-3, 10 MW) became internationally known for its capability to test refabricated fuel rods, which enabled, among other things, the determination of fuel performance behaviour (mainly fission gas release and thermal conductivity) of high burn-up fuel. This unique capability consisted of cutting a high burn-up segment out of a high burn-up fuel, defueling the upper and lower end of the fuel segment, drilling a centre hole in the fuel, inserting a thermocouple in the centre hole and refilling the rod with filler gas at predetermined pressure and re-welding the rods. As will be discussed below, these Risø capabilities were absorbed by Halden when the Risø fuel programme was ended (and the reactor subsequently closed in 2000).

Other RRs, mostly operated in the frame of national programmes, have given important contributions to international R&D in the past, such as the SILOE and the Osiris reactor in France, the National Research Universal (NRU) reactor in Canada and the Japan Materials Testing Reactor (JMTR) in Japan. These RRs have been permanently shut down during the last decade. Similar trends occurred in smaller reactor facilities in other countries.

When these reactors were dismissed, or their use for fuel assessment terminated (as in the case of HFR), some of their key competences were taken over by Halden, a process that normally required technology upgrades and adaptations. For instance, the HBWR was not well suited for power ramps, and in fact power ramps had practically never been carried out at Halden on pre-irradiated commercial fuel before the 1990s. But when the HFR stopped the ramp testing and especially when the Swedish R2 reactor was shut-down, Halden inherited the power ramp duty. Among others, this required important efforts to create local HBWR core conditions with high thermal flux, which were needed for ramps with high burn-up commercial fuel.

After the Risø reactor closure, the high burn-up rod re-fabrication capabilities were transferred to Halden through a Risø-Halden collaboration agreement. This technology upgrade (i.e. the fuel re-fabrication/instrumentation capability) has been a fundamental step for Halden, in that it favoured the installation of a number of fuel tests on various performance and safety issues, including high burn-up fuel performance, secondary fuel failure degradation, cladding corrosion, hydriding as well as LOCA.

The Studsvik R2 capabilities for high burn-up overpressure tests were also inherited and improved at Halden, in that on-line measurements of the fuel centre temperature and of the rod diameter profile were added to the test menu. The Halden overpressure tests (IFA 610 series) enabled the direct measurement of the pellet-cladding mechanical interaction (PCMI) (through on-line diameter profilometry) during operation and were used to quantify the feedback on fuel temperature as cladding creep-out occurred.

The combination of re-fabrication capabilities and Halden's instrumentation skills has been very beneficial, not only for testing high burn-up fuels, but also for testing of (pre-irradiated) materials relevant for assessments of reactor internals ageing. These primarily consisted of studying stress corrosion cracking initiation and propagation for a variety of materials and as affected by the radiation dose and water chemistry environment. Crack initiation and crack propagation were monitored on-line with special sensors (such as the potential drop instrumentation) installed on pre-irradiated specimens prior to the HBWR testing.

Starting from the 1990s, reactor material testing became a key area for Halden, to the point that at several times, material tests prevailed over fuel tests in terms of the number of irradiation rigs. Among others, this required important technical developments at Halden in water chemistry monitoring and control systems and – as said above - in the field of on-line detection of stress corrosion cracking and crack propagation. Rather than "*science*", the main drive for such developments was the industry need to build a technical basis for plant life extension, as well as the need from licencing organisations for data able to support regulation for extended reactor lifetime.

It should also be mentioned that, in addition to the RRs mentioned above, pulse reactors such as Cabri in France and the Nuclear Safety Research Reactor (NSRR) in Japan were dedicated to RIA safety test programmes that were shared internationally – the Cabri under the umbrella of an OECD-NEA Agreement and the NSRR through a national programme with results shared internationally. The Cabri testing resulted in a total of 14 LWR tests run (in Na environment) between 1991 and 2005. The NSRR took over the role of RIA testing after Cabri was shut-down for a long-term refurbishment, producing a total of 62 tests on LWR-irradiated fuel, which is almost 50% of the overall LWR RIA database. At its maximum, NSRR produced about four tests per year. The Cabri reactor has resumed testing in pressurised water environment, and the NSRR, which has been shut-down since 2012, is also intended to restart operation.

The TREAT reactor at INL has been refurbished recently with the aim of resuming a RIA tests programme. The TREAT Pressurised Water Loop which is requested to test LWR irradiated fuel rodlets in prototypical conditions has not been built yet.

## 5. Note on the Halden reactor

The Halden reactor was not constructed for performing the range of tests that it was able to accommodate at the time of its closure. In fact, it was not even meant to be a test station of the sort it became, but rather a prototype of a process steam generator for the (paper) industry. The evolution towards large scale testing facility occurred rapidly but smoothly – thanks to the synergy that was developed between users and the HBWR establishment through the OECD Halden Reactor Project (HRP).

The creation of the OECD HRP was in fact the very basis for the continued operation of the Halden reactor throughout its entire 60 year lifetime. In addition to providing a predictable source of financing, the HRP facilitated the creation of a stable and trustworthy relationship between the reactor and its users, through the "invention" of two parallel entries. These were the so-called HRP Joint Programme (co-financed by many countries under the auspices of the OECD/NEA) and the so-called Bilateral Projects, which were basically a cluster of experiments, each one contracted with a single user – and paid for by such user – within the Joint Programme family. The tests for the Joint Programme and for the Bilateral Projects were run in parallel with each other in most cases.

The synergy between the Joint Programme and the Bilateral Projects has made the technological fortune of the HBWR, generating a solid technical basis through continued and deep interaction with the industry, the safety bodies and the R&D centres around the world. In normal times, as many as 20 to 30 experiments were run at the same time in the HBWR, which is an unprecedented performance on a global basis. These tests addressed most of the fuel and material performance studies of interest, apart from RIA tests, which could not be run in the HBWR.

The main factors that made this possible were as follows:

- Robust reactor design and flexible operating conditions, in particular by the large core and the interchangeability between test rigs and driver fuel assemblies. There are as many as 100 positions, in principle, available for testing, depending on conditions.
- Large space available due to the use of heavy water as core coolant and moderator, which enabled the accommodation of test equipment and instrumentation around the test fuel and materials.
- Relatively high water operating temperature, i.e. 240°C (34 bar pressure). This gave a considerable advantage as compared to other RRs, in that the HBWR coolant temperature was only 40-60°C below the one in LWRs, compared with a difference of about 230-250°C for other RRs. For some testing (e.g. for fuel thermal conductivity assessments or for fission gas release (FGR) determinations), the HBWR coolant temperature was close enough to LWR temperature conditions that operation in a special water loop could be avoided.
- No reflector material was used in the HBWR. A wide heavy water gap between the fuel region and the vessel, created the conditions for a very low irradiation damage rate of the vessel.
- In-house fuel fabrication capability, and use of $UO_2$ fuel of commercial origin, enabled Halden to maintain control on reactor fuel cost, quality and delivery time.
- Shortcomings due to the relatively low fast neutron flux were (partly) overcome by using so-called booster rigs, which contained a large number of fuel rods packed within the test rig around a relatively small region where the test specimens were located. Similarly, high thermal flux (such as for power ramps) were obtained by arranging a circle of high power assemblies around the ramp test rig. These arrangements had, however, a price in terms of demanding fuel operation and control.

While Halden could do most of the testing required for nuclear reactor safety and reliability, it could not do everything. As already mentioned, RIA tests were beyond Halden's reach, while power ramps were at the edge of what the HBWR was able to perform. But altogether, important and unique test combinations were made possible through an enhanced use of the reactor and of test instrumentation, which occurred gradually and over a long period of time. The test variety helped maintain a stable income and solid economy for long time – which, in turn, favoured investments and new developments, as long as sound management was present.

Trying to imitate Halden in doing much, if not all, testing in one place, is probably very difficult and would take a long time. Alternatively, few research reactors dedicated to specific tasks may be considered, at least until one or some reactors overtake the hegemony in fuel and material testing.

## 6. Possibilities with RRs in the future

In addressing the future of fuel and material testing needs and how these needs can realistically be accomplished, one can first make an appraisal of what can believably be achieved with currently operating test reactors. Keeping in mind that further discussions with concerned organisations can impact the assessment of the situation, possibilities to exploit RRs in the near future can be summarised as follows:

- The BR2 may perform limited fuel testing. However, not much customer-related LWR fuel/material testing is currently being performed. While this may change in the future, the amount of LWR fuel testing in BR2 will probably be small, at least for the next five years or so (apart from an EU programme called "Il Trovatore" which is anyway limited and not further addressed here). Power Ramp tests can only be performed during the inter-cycles because the power increase is generated by the core itself (i.e. the other experiments in the core have to be unloaded during the power ramp test).
- The use of the Advanced Test Reactor (ATR) in the United States for commercial fuel/material testing was announced one or two decades ago, but never really materialised.
- For RIA testing, the Cabri and the TREAT reactors are to be or may be restarted. The Cabri reactor may produce two to four RIA tests per year. TREAT capabilities for the international community are to be clarified. The Cabri/TREAT capabilities for tests other than RIA, such as for LOCA tests, remain to be demonstrated.
- The Hanaro reactor in South Korea is not used for fuel testing.
- RIAR, with MIR.M1, SM3 and BOR60 offers a complete variety of test facilities (LOCA, power ramp tests, irradiations tests in MIR, high flux material irradiations in BOR60). International experiments are ongoing but shipments, legal and contractual frameworks are difficult to handle. NEA is undertaking investigations into how these issues could be addressed.
- The JHR reactor will likely be ready for testing in five to six years from now and its actual test capability will need to be demonstrated. Test rigs to cover power ramp testing, LOCA tests, instrumented irradiation in LWR test conditions, material irradiation are under construction and will be available at the RR start or right after.
- The HFR in the Netherlands performed some fuel and material testing though requires major investments in both testing rigs and staff.
- The test reactors in Poland, Czech Republic and Hungary may be considered, especially for some material testing, included non-fuelled cladding irradiations.

Based on the above, a concise overview is made on what can be done in the near future in the area of fuel and material testing for water reactor purposes. This overview is presented below.

## 7. Base irradiation of fuel rods

Virtually all fuel tests requiring some level of burn-up need a base-irradiation phase prior to on-site inspections, or prior to hot cell examinations or prior to testing in an RR. Base irradiation can be carried out in a commercial NPP or in an RR. However, in practice, most base irradiations are made in NPPs, as these provide the most representative conditions and better efficiency in terms of time to achieve the target burn-up. NPP base-irradiations have in the past been used in preparation of a number of specialised fuel tests carried out in RRs, after the desired burn-up had been achieved. At Halden, for example, at a time of "normal" test inventory, about 50% of fuel testing was carried out with fuel base irradiated in an NPP. Most of RIA tests were also carried out with fuel specimens originating from NPPs.

It is important that in a period when the RR offers of tests are scarce or lacking, the industry maintains continuity with new developments – and that pertinent base irradiations in selected

NPPs continue to be carried out. These base irradiations may address the items mentioned above or other subjects that the industry deems important. By doing this one will be able to at least produce fuel performance data in realistic NPP normal operation conditions, while creating the conditions for exploring beyond normal operating conditions through tests in RRs. The availability of suitable pre-irradiated specimens would in fact favour both the promotion of PIE work and the implementation of new specialised tests in RRs.

In the past, power reactors such as Ohi, Mihama-2 and others in Japan, M Guire in the United States, Forsmark, Oskarshamn-3 and Ringhals-2,-3,-4 in Sweden, Beznau, Gosgen and Leibstadt in Switzerland, Vandellos-2 in Spain, and Paluel-1, Graveline-2,-4,-5 and Laurent B-1 in France have been used to provide the fuel rods from which specimens for RR experiments were derived. These were used for power ramps, RIA testing, LOCA testing and other high burn-up testing. Obviously, the presence of suitably large hot cells in the same country where the fuel base irradiation is carried out would constitute a great advantage.

*The NEA may provide an overview of power reactors where experience and interest exist for base irradiations of fuel to be subsequently handled for PIE and/or further RR testing. Associated hot cell capabilities should also be outlined. Where suitable, the NEA may also favour the continuation of existing programmes, or the creation of new ones, involving NPP irradiations and PIE, through establishing international projects.*

## 8. Base irradiation of unfuelled cladding

For studies of new types of cladding, a preliminary stage may be required prior to fuel testing, in order to study material properties and demonstrate the material suitability before moving on towards fuel rod irradiations. This preliminary stage normally encompasses out-of-pile testing in autoclaves or loops, followed by reactor irradiations of unfuelled cladding specimens, which can provide valuable information regarding dimensional changes under stress conditions, irradiation growth, waterside corrosion and hydriding. Hot cell post-irradiation testing of the pre-irradiated specimens would in addition provide important insights regarding mechanical properties (e.g. tensile) or capability to withstand LOCA transients.

Normally, such cladding base irradiation requires rather high fast neutron flux, typically close to 1.e14 n/cm$^2$s or higher, and temperatures close to LWR operating temperature. Experience exists for performing cladding base irradiation both in power plants and in test reactors. As an example, irradiations of cladding and guide tubes specimens have been carried out in the guide tubes of the Chinon NPP in the late 1990s, providing hundreds of irradiated coupons of various alloy concepts. Some of the samples were machined prior to the irradiation to allow mechanical properties tests of the irradiated specimens without further geometrical modification. An experimental irradiation of cladding specimens is on-going at Temelin reactor in the Czech Republic. Similar high-flux irradiations are possible in a number of NPPs as well as in a number of test reactors. For the latter ones, a challenge would be to provide the right fast flux, water temperature, pressure and chemistry conditions, in case of wet irradiations.

*The NEA may provide an overview of power reactors and RRs where experience is readily available for base irradiations of unfuelled cladding or guide-tubes material, to be subsequently used for PIE or post-irradiation testing (in-pile and out-of-pile).*

## 9. Base irradiation of reactor internals

Much of what is said for irradiations of unfuelled cladding applies also to irradiations of steel reactor internals. Also in this case, in fact, irradiations can be wet or dry, and can be done in NPPs or in test reactors. Typical testing includes crack initiation and crack growth as affected by materials and load. These can be conducted both in a NPP (with static loading, pre-existing water chemistry conditions and outage inspections) or in an RR (with on-line monitoring, with variable loading and/or variable water chemistry).

An important aspect may be constituted by the specimen size, which may be larger for reactor internals as compared with cladding specimens, which depends on what type of test is to be carried out.

It should also be noted that a considerable amount of irradiated internals material should be available following removal of such material from NPPs undergoing decommissioning.

*The NEA may provide an overview of power reactors and RRs where experience is readily available for base irradiations of steel materials (internals), to be subsequently handled for PIE or for post-irradiation testing. An overview of irradiated internals extracted from NPP in the past and currently available should also be provided.*

## 10. In-pile tests that can only be done in an RR

It has already been mentioned that a number of nuclear fuel and material assessments may require NPPs in order to carry out the base irradiation prior to PIE or post-irradiation testing. There are situations, however, where NPPs cannot be used – either for base irradiations or for testing. These include the following situations:

- Any fuel base-irradiation or testing that involves fuel materials or fuel assembly arrangements for which operational experience is scarce and/or for which operational licence is not available or hard to obtain. This includes, for instance, exotic, cladding materials, non-$UO_2$/non-MOX fuels, or fuel geometries that differ substantially from those for which operational experience exists. Segmented fuel rods may be licensable in some cases and not in others, depending on safety authority requirements and previous experience.
- Assessments of fuel operational limits, i.e. of fuel behaviour at conditions beyond normal operation or at conditions for which operational experience does not exist or is scarce, as well as investigations of fuel behaviour in accident situations
- Fuel irradiations requiring water chemistry type for which operational experience does not exist or is scarce and which may lead to excessive cladding corrosion or hydriding. This also concerns irradiation and water chemistry effects on stress corrosion cracking of internals materials.
- Tests that require in-reactor instrumentation placed on the test specimens, such as for on-line monitoring of fuel temperature, FGR in fuel rods or crack propagation rate in stress corrosion cracking tests for internals.

The category of specialised tests addressing operational limits may include one or more of the following items:

- power ramps for fuel failure limit assessments;
- slow-rate power increments, including cladding strain assessments;
- fuel behaviour under power cycling and load following conditions;

- FGR vs power and burn-up;
- fuel thermal behaviour at high burn-up (thermal conductivity degradation);
- margin to fuel melting;
- rod overpressure effects on cladding deformation, fuel temperature and FGR;
- cladding corrosion build up and hydrogen pick-up fraction at high burn-up;
- LOCA tests at medium and high burn-up;
- RIA tests at medium and high burn-up;
- ultra-high burn-up phenomena.

The above investigations normally require hot cell work for:

- PIE of the base-irradiated fuel;
- preparation of the actual fuel specimen prior to the specialised tests in an RR;
- final PIEs after the specialised tests in an RR.

An overview of fuel and reactor material performance studies foreseen in the future is provided in Tables 1 and 2 in Section 2. An indication as to whether the irradiation can be done in a NPP or in an RR is also given. The shaded areas relate to items having higher priority and for which irradiation in an RR is required. In addressing RR projects for the future, these are considered as the most important ones.

*Appendix 1*

**Brief Summary of the Workshop on "Enhancing Experimental Support for Advancements in Nuclear Fuels and Materials"**

**8-10 January 2018**

OECD Headquarters,
OECD Conference Center, Room CC15
2, rue André Pascal Paris, France



## Opening Session

The workshop was opened by the NEA Director General (DG) Bill Magwood and the Chair John Herczeg, Deputy Assistant Secretary at the US DoE. They gave their remarks in order to set the context of the meeting and express the overall direction of the NSC in this area, with this workshop providing the first step. The Chair provided the participants with a summary of the objectives and explained the format of four sessions, each with an intermediate wrap-up, followed by a comprehensive closing session on the third day. The complete workshop agenda may be found in Appendix 2 and the list of participants in Appendix 3.

## Session 1: Industry (presentations from EDF, Exelon, TVEL, Global Nuclear Fuel, Westinghouse Electric Company, ČEZ, Mitsubishi Nuclear Fuel Co, Toshiba Energy Systems & Solutions Corporation and Vattenfall Nuclear Fuel AB)

The presentations encapsulated the industry experiences and perspectives in fuel and materials evolution. In the current state of play industry efforts for advanced fuels are focused on design changes driven by both safety and economics. Furthermore, there are widespread global activities focused on advanced fuels with many differing stakeholders (vendors, utilities, labs, regulators). Accident Tolerant Fuel (ATF) implementation is moving at an accelerated pace – balancing the needs of speed to market vs. 100% design certainty. Designs for ATF exist as both evolutionary and revolutionary concepts. Finally, it was noted that several innovations can be combined together to provide a more valuable overall solution – in terms of enrichment, burn-up, mitigation, etc.

Common needs were identified by several speakers; firstly, both modelling tools and their supporting experimental data are needed – covering an understanding of both the knowledge gaps and the experimental and modelling capabilities. Clear needs for a framework for use of international testing facilities (transport, disposal, etc.) and to promote international regulatory alignment for new fuel materials were also recognised. The establishment of a sound collective international collaboration was promoted, since no one entity was envisaged to achieve success on their own.

To address these needs, potential actions were highlighted – for instance formation of a group to prioritise needs for validation/qualification of new fuels and materials. In addition, a platform could be built to establish links between the needs identified and the experimental and modelling capabilities available. This could possibly be part of an international collaborative effort to address generic questions or linked to a framework for promotion of more efficient use of international resources (transport, disposal, etc.). Furthermore, it was suggested that a specific database of testing materials available for collective use could be developed.

## Session 2: R&D (presentations from IBRAE, ORNL/RSICC, CEA, EPRI and EDF)

Presentations were made on advances in nuclear science, concerning promising fuel technologies, modelling and validation methods and associated experimental challenges. Currently in R&D, there is a focus on improvements to mechanistic modules of existing fuel performance codes using multi-scale modelling. However, these are based upon the existing experimental suite for standard nuclear fuels. It was noted that a broad range of promising concepts are being investigated (fuels, clads, core materials), all with identified safety/economic advantages to industry and that efforts are on-going to analyse these concepts in greater depth so as to be able to quantify improvements in operational/safety margins. Overall, there were consensuses that more work needs to be done on validation, for a predictive capability and sensitivity/uncertainty quantification.

Several conclusive issues were noted by the participants; firstly that improved physics modelling allows experimental selection and design that may be able to guide targeted experiments and programmes. Potentially, a wide set of experimental data may be useful to validate/fine tune the fundamental modelling parameters. However, in the absence of well quantified uncertainties the applicability of legacy experiments remains difficult. Furthermore, the validation process needs to be well established to efficiently link to an experimental programme; not all regions of experimental space can be measured in a pointwise fashion, thus there are situations that need simulation to fill in values, i.e. the tensor field. It was also asserted that linkages between groups are important in helping to identify the different needs of industry, vendors, R&D, and facilities. Concerning ATF, their optimisation is dependent on all surrounding components and conditions; the problem has many variables and is a case of non-linear optimisation.

The importance of the Phenomena Identification and Ranking Table (PIRT) process was made particularly clear. This can be used as a mechanism to efficiently identify generic issues across proposed near and long term concepts and can enhance risk informed prioritisation of R&D. Transparency between stakeholders in the PIRT process also assists in building confidence in the overall process. Other recommendations included updating the existing database of Integral Fuel Performance Experiments (IFPE) with the new testing data, allowing validation of fuel performance on the atomistic scale. Enablement of data and model sharing from experiments and simulations that do not involve proprietary information was also encouraged. Finally, there was a proposal to develop a working arrangement with tighter coupling between experimentalists and modellers, focusing on issues relevant to stakeholder needs (vendors, utilities, regulators).

## Session 3: Technical Support Organisations (TSO) (presentations from NRC, JAEA, Rostehnadzor and IRSN)

The representatives of the TSOs expressed their perspectives concerning the operation of current and innovative fuels and materials. At the present time, regulators and TSOs are actively anticipating how new fuels/materials can be progressively licensed under the existing frameworks or frameworks adapted as appropriate to new concepts. A cautious, phased approach, with enough time to sufficiently adapt processes and incorporate feedback is preferred. Generally, they are in support of the emphasis of fuels testing in MTRs as critical towards introduction to NPPs. It was also affirmed that the safety level of new fuels should be at least equivalent to the current fuels, not only for normal operation and Design Basis Accidents (DBA) but also for beyond design-basis accidents and Severe Accidents (SA).

The needs of TSOs were also summarised in the following ways: safety behaviour of fuels is an area where collaboration is needed, which reiterates the importance of extensions of existing collaborations for ATF. Also, the balance between safety benefits and economic benefits is clearly important to engage both industry and policy makers. The goals should be to take advantage of new instrumentation, experimental techniques and modelling for the optimisation of the development process; and, to ensure consistency between safety criteria and measurements/computations, i.e. local values vs. global values.

Many potential actions which would lead towards acceleration of fuels/materials deployment were identified. Briefly, these included a recommendation to test several options simultaneously to mitigate the risks associated with the failure of one option. There is also a clear need to carefully design and perform the "right" experiments. The development of an advanced experimental approach (on-line measurements, sensors etc.) was encouraged, especially for IET, as was the introduction of advanced modelling. Critically, the early involvement of regulators and TSOs should be ensured, to take part in identification of gaps in experimentation and definition of experimental programmes. This should also go in hand with making optimal use of existing data and performing new experiments to address identified experimental gaps. Strong interaction between regulators and industry to discuss safety requirements and criteria was especially highlighted, as well as the advantage in identification/harmonisation of safety requirements and criteria at the international level. This therefore should encourage further cross-fertilisation between the NSC and CSNI (WGFS) activities in the area of fuels/materials development.

## Session 4: Infrastructure (presentations from RIAR, NSUF, IFE/Halden, CEA, INM, IRSN and INL)

An overview of currently operating and being-built experimental infrastructure was offered by the speakers. International test reactors were presented, including: MIR M1, BOR60, SM3, Halden, JHR, BR2, HFR, LVR15, IVV 2M, TREAT and CABRI. In addition, material databases and collections, PIE hot-labs and irradiation facilities were also covered in some depth.

From these presentations and the following discussions, several points were reinforced. Firstly, was the critical need to maintain the existing network of facilities for testing of fuels and materials (irradiation and hot-lab capacities). This network will help to ensure the continuity of services in the event of long-term programmes. Also, there was the need to develop more analytical experimental capabilities, comprising in-situ, real-time, microscopic, and highly accurate measurements to feed advanced modelling; in the context of computational methods making steady progress, there is a need to synchronise the progress of advanced instrumentation accordingly. As a supporting block to any such testing programme, an issue associated with the complexity of international transport and the back-end experimental samples was raised. Finally, technical needs and updates to basic fuel data were specified – i.e., those triggered by safety demonstration requirements, operational flexibility and reduced time for deployment.

To address the future needs discussed, actions to be considered were put forward. Primarily, the recommendation was to organise multilateral and multinational experimental programmes for qualification/validation of evolutionary and revolutionary fuel/cladding concepts and structural materials. Second to this was the potential establishment of focused frameworks; to facilitate pooling/networking of experimental infrastructures, sharing of techniques and development/implementation of advanced instrumentation; to organise cross-benchmarking (for techniques and procedures), or; to allow the linking of the experimental data resulting from these networks through advanced modelling for the benefit of the end-users. It was also suggested that a High Level Group (HLG) or equivalent be formed to address difficulties associated with international transport and the back-end experimental samples.

## Closing Session

The closing session was opened first with a presentation by Fiona Rayment (NNL) and Daniel Iracane (NEA DDG) on the NI2050 concept and the influence of this workshop on the innovation program, cross-cutting several NEA committees. This was followed with a wrap-up presentation summarising the conclusions, needs and potential actions from each of the four workshop sessions. Finally, the Chair closed the workshop, acknowledging required actions which would be addressed to the NSC in their meeting during the following days, these included:

- Formation of a group to prioritize needs for validation/qualification of new fuels and materials.
- Building a platform to establish links between the needs identified and the experimental and modelling capabilities available.
- Promotion of a framework or high level group for more efficient international practices in transport, disposal and back-end handling of samples.
- Enablement of data and model sharing from experiments and simulations that do not involve proprietary information.
- Development of a working arrangement with tight coupling between experimentalists and modellers, focusing on issues relevant to stakeholder needs (vendors, utilities, regulators).
- Ensuring the early involvement of regulator and TSO to identify gaps in experimentation and to definition of experimental programs.
- Identification/harmonisation of safety requirements and criteria at the international level.
- Encouraging further cross-fertilization of the NSC and CSNI (WGFS) activities in the area of fuels/materials development.
- Organisation of multi-lateral and multi-national experimental programs for qualification/validation of evolutionary and revolutionary fuel/cladding concepts and structural materials.
- Establishment of formal frameworks to:
    - facilitate pooling & networking of experimental infrastructures, sharing of techniques and development implementation of advanced instrumentation;
    - organize cross-benchmarking for techniques & procedures;
    - allow the linking of the experimental data resulting from experimental networks through advanced modelling for the overall benefit of end-users.

*Appendix 2*

# Participant List of the Workshop on Enhancing Experimental Support for Advancements in Nuclear Fuels and Materials

## 8-10 January 2018

## Day 1 Monday, 8 January 2018
12:30 – 17:45

Workshop chair: **John Herczeg,** Chairman of the Nuclear Science Committee, Deputy Assistant Secretary, USDOE

### OPENING SESSION
12:30-12:50

- **William D. Magwood, IV**, Director-General of the Nuclear Energy Agency (NEA)
- **John Herczeg**, Chairman of the Nuclear Science Committee, Deputy Assistant Secretary, USDOE

### SESSION 1: INDUSTRY EXPERIENCE AND PERSPECTIVES IN FUEL AND MATERIALS EVOLUTION
12:50-17:45

**Chair: Randy Stark**, Director, Fuels & Chemistry, Electric Power Research Institute (EPRI), USA

**Co-chair: Phillip Finck**, Senior Scientific Advisor, Idaho National Laboratory (INL), USA

**Speakers:**

- **Michel Maschi**, Vice President EDF R&D Generation and Engineering, Électricité de France (EDF), France
- **Ken Petersen**, Vice President, Nuclear Fuels at Exelon Nuclear, USA
- **Alexey Dolgov**, Director of R&D Department, Joint-Stock Company TVEL, Russia
- **Kevin Ledford**, Senior Manager of Fuel Technology, Global Nuclear Fuel, USA

**Coffee Break 14:10-14:30**

- **Jonathan Wright,** Manager Materials and Fuel Rod Design, Westinghouse Electric Company, USA
- **Rostislav Štaubr**, Nuclear Fuel Manager, Fuel Cycle Unit, ČEZ, Czech Republic
- **Hideyuki Teshima**, Deputy General Manager, Fuel and Core Engineering Department, Fuel Engineering Division, Mitsubishi Nuclear Fuel Co, Ltd., Japan
- **Kazuo Kakiuchi**, Senior Specialist, Toshiba Energy Systems & Solutions Corporation, Japan
- **David Schrire**, Specialist in Fuel Performance, Vattenfall Nuclear Fuel AB, Sweden

**Coffee Break 16:10-16:30**

**Panel discussion 16:30 – 17:45**

**Cocktail Reception (starting at 17:45, G. Marshall)**

## Day 2 Tuesday, 9 January 2018
9:00-18:00

## SESSION 1: INDUSTRY EXPERIENCE AND PERSPECTIVES IN FUEL AND MATERIALS EVOLUTION (CONT'D)
9:00-9:50

**Chair: Randy Stark**, Director, Fuels & Chemistry, Electric Power Research Institute (EPRI), USA

**Co-chair: Phillip Finck**, Chief Scientist, Idaho National Laboratory (INL), USA

- Summary and conclusions by session chair
- Wrap-up discussion towards conclusions and actions
- **Nicolas Waeckel**, Corporate Expert on Fuel Design and International R&D, Engineering Division, Électricité de France (EDF), France
  *"Nuclear fuel R&D facing new paradigms to address industrial needs"*

## SESSION 2: ADVANCES IN NUCLEAR SCIENCE: PROMISING FUEL TECHNOLOGIES MODELLING AND VALIDATION METHODS AND ASSOCIATED EXPERIMENTAL CHALLENGES
9:50-13:00

**Chair: Kemal Pasamehmetoglu**, Associate Laboratory Director, Idaho National Laboratory (INL), USA

**Co-chair: Alexander Tuzov**, Director, Joint-stock Company "State Scientific Center - Research Institute of Atomic Reactors" (JSC SSC RIAR), Russia

**Speakers:**

- **Leonid Bolshov**, Scientific Leader, Academician, The Nuclear Safety Institute of Russian Academy of Sciences (IBRAE RAS), Russia
- **Timothy Valentine**, Director, Radiation Safety Information Computational Center, ORNL/RSICC, USA
- **Carole Valot**, Research Engineer,
  **Jean-Christophe Brachet**, Research Engineer,
  Commissariat à l'énergie atomique et aux énergies alternatives (CEA), France

**Coffee Break 10:50-11:10**

- **Al Csontos**, Technical Executive, Fuel Reliability & High-Level Waste, EPRI, USA
- **Masaki Kurata**, Senior Principal Researcher, Division Leader, Debris Characterization & Core Status Evaluation Division, Collaborative Laboratories for Advanced Decommissioning Science (CLADS), Japan Atomic Energy Agency (JAEA);
- **Marie Moatti**, Executive, Fuel Economy and Safety, Nuclear Fuel Division, Électricité de France (EDF), France

**Panel Discussion 11:50 – 13:00**

**Lunch Break 13:00-14:00**

## Day 2 Tuesday, 9 January 2018 (cont'd)
9:00-18:00

## SESSION 3: TECHNICAL SUPPORT ORGANISATIONS' PERSPECTIVES FOR OPERATION OF CURRENT AND INNOVATIVE FUEL AND MATERIALS
14:00 – 17:00

**Chair: Jean-Christophe Niel**, Chair of the Committee on the Safety of Nuclear Installations (CSNI), Director-General, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France

**Speakers:**

- **Mirela Gavrilas,** Director, Division of Safety Systems, Nuclear Regulatory Commission (NRC), USA
- **Kunio Onizawa**, Director, Planning and Coordination Office, Sector of Nuclear Safety Research and Emergency Preparedness, Japan Atomic Energy Agency Nuclear Safety Research Center (JAEA), Japan
- **Valery Pivovarov**, Leading Scientist, Rostehnadzor, Russia
- **Olivier Marchand**, Deputy Head of Department, Department of management of incidents and accidents, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France

**Coffee Break 15:40-16:00**

**Panel Discussion 16:00 – 17:00**

## INTERMEDIATE SESSION
17:00 – 17:30

- **Carlo Vitanza**, NEA Consultant, *"Sharing experience with NEA Joint Projects"*

## SESSION 4: EXPERIMENTAL INFRASTRUCTURE: PERSPECTIVES IN ADVANCED INSTRUMENTATION AND EXPERIMENTAL TECHNIQUES TO SUPPORT FUEL DEVELOPMENT
17:30 – 18:00

**Chair: Hamid Ait Abderrahim**, Deputy Director-General, Belgian Nuclear Research Centre (SCK.CEN), Belgium

**Co-chair: Nicolas Waeckel,** Corporate Expert on Fuel Design and International R&D, Engineering Division, Électricité de France (EDF), France

**Speakers:**

- **Alexander Tuzov**, Director, Research and Science Joint-stock Company "State Scientific Center - Research Institute of Atomic Reactors" (JSC SSC RIAR), Russia

## Day 3 Wednesday, 10 January 2018
9:00-15:30

## SESSION 4: EXPERIMENTAL INFRASTRUCTURE: PERSPECTIVES IN ADVANCED INSTRUMENTATION AND EXPERIMENTAL TECHNIQUES TO SUPPORT FUEL DEVELOPMENT (CONT'D)
09:00 – 12:50

**Chair: Hamid Ait Abderrahim**, Deputy Director-General, Belgian Nuclear Research Centre (SCK.CEN), Belgium

**Co-chair: Nicolas Waeckel,** Corporate Expert on Fuel Design and International R&D, Engineering Division, Électricité de France (EDF), France

**Speakers:**

- **Rory Kennedy**, Director of the US DOE Nuclear Science User Facilities (NSUF) Program, Idaho National Laboratory (INL), USA
- **Scott Holcombe**, Manager, Research and Development Department, Institute for Energy Technology/The Halden Reactor Project (IFE/HRP), Norway
- **Alexey Izhutov**, Deputy Director, Research and Science, Joint-stock Company "State Scientific Center - Research Institute of Atomic Reactors" (JSC SSC RIAR), Russia
- **Gilles Bignan**, User Facility Interface Manager, Jules Horowitz Research Reactor (JHR) Project, Commissariat à l'énergie atomique et aux énergies alternatives (CEA), France
- **Konstantin Koshcheev,** Chief Specialist, Science and Innovation Development Department, Joint-stock Company "Institute of Nuclear Materials" (JSC INM), Russia

**Coffee Break 10:40-11:00**

- **Christelle Manenc**, Project Leader of Experimental Program on Cabri Reactor, Department of Experimental Research, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France
- **Phillip Finck**, Senior Scientific Advisor, Idaho National Laboratory (INL), USA

**Panel Discussion 11:40 – 12:50**

**Lunch Break 12:50-13:50**

## Day 3 Wednesday, 10 January 2018 (cont’d)
9:00-15:30

## CLOSING SESSION
13:50 – 15:30

**Chair: John Herczeg**, Chair of the Nuclear Science Committee, Deputy Assistant Secretary, USDOE

- **Fiona Rayment**, Executive Director, Nuclear Innovation and Research Office (NIRO) National Nuclear Laboratory (NNL), UK
- **Daniel Iracane**, Deputy Director-General and Chief Nuclear Officer, NEA *“Towards Nuclear Innovations 2050 (NI2050)”*
- **Conclusions by session chairs and workshop chair and discussion**
- **William D. Magwood, IV**, Director-General of the Nuclear Energy Agency (NEA) Closing remarks

## *Appendix 3*

# Participant List of the Workshop on Enhancing Experimental Support for Advancements in Nuclear Fuels and Materials

## 8-10 January 2018

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