Halden Reactor Project Activities, Achievements and International Collaboration

W. Wiesenack

OECD Halden Reactor Project, Institutt for Energiteknikk, Norway

1. Introduction

The OECD Halden Reactor Project has contributed for many years with R&D programmes devised to provide data for the safe and reliable operation of nuclear power plants in a direct and effective manner. The Halden Project's international profile and solid technical basis represent an asset for the nuclear community at a time in which maintaining centres of expertise at accessible cost becomes increasingly important.

The OECD Halden Reactor Project constitutes an international network with currently 18 member countries. The organisations participating in the Halden Project represent a complete cross section of the nuclear community, including licensing and regulatory bodies, vendors, utility industry and research organisations. The R&D work is defined in the Joint Programme, which is renewed every third year and financed by the participating countries - with Norway as host country covering a significant fraction of the budget. A number of organisations in the participating countries execute their own development work in collaboration with the Halden Project. These bilateral arrangements constitute an important complement to the Joint Programme.

The research programmes generate key information for safety and licensing assessments and aim at providing:

- Basic data on how the fuel performs in commercial reactors, both at normal operation and in transient conditions, with emphasis on extended fuel utilisation.
- Knowledge of plant materials behaviour under the combined deteriorating effects of water chemistry and nuclear environment.
- Advances in computerised surveillance and operator support systems, human factors and man-machine interaction.

All of these are judged important for steadily improving generation economics and flexibility of nuclear power plants in a competitive and deregulated electricity market, at the same time maintaining the safety standards in effect for nuclear power stations worldwide. This paper concentrates on the Halden Project research programme related to fuel testing. An overview of ongoing tests on WWER fuel performance is also included.

2. Overview of the Halden Reactor Project

2.1. International and National Organisation

The Halden Reactor Project is hosted by Institutt for Energiteknikk, Norway, and organised under the auspices of the OECD Nuclear Energy Agency. The activities of the Joint Programme are agreed upon for a period of three years, the current one going from 2003-2005.

An international committee, the Halden Board of Management, approves the research and experimental programme, which is prepared and executed by a team of scientists and engineers, many of them drawn from the various participating countries. An international technical group, the Halden Programme Group, is appointed for supervision of the programme. The Board and Programme Group each meet twice a year, and special emphasis is given to the autumn meeting where the details of the programme for the next year are defined. Twice in a three-year periods, an Enlarged Halden Programme Group Meeting is held. This is a sizeable conference where results both from the Halden Project and from participating organisation are reported.

For performing the research, the Halden Project has about 280 employees including about 90 university graduates and about 15 foreign experts seconded to the Project from member organisations. They represent an important factor for introducing innovative elements in the Project work scope. An increasing number of seconded arrangements involve young scientists, reflecting a growing educational role of the Halden Project. This is integrated with practical and analytical work in the context of the Project programme and gives a valuable contribution to maintaining relevant nuclear competence in member organisations. Also in this context, an international Summer School is being arranged once a year in collaboration with the OECD Nuclear Energy Agency. The contents alternate between subjects from the Fuels&Materials and Man-Technology-Organisation (MTO) research. The next summer school in August 2004 will be devoted to fuel performance modelling.

Performance studies on light water reactor fuels and materials, human factors studies and development of computerised supervision and control systems have been the main activity areas in the research and development programme. The Halden Project will also in the years to come concentrate on the effective utilisation of the reactor (HBWR) for fuels and materials characterisation and on the Halden Man-Machine Laboratory (HAMMLAB) for human factors and control room advances.

Being a member of the Halden Reactor Project gives access to the results and products of the Joint Programme, also those obtained in the past. In addition, the Halden Project facilities can be used for R&D work on a bilateral basis. Discussions have taken place between Bulgaria and the Halden Project regarding participation in the current programme period, and a positive conclusion is about to be reached.

2.2. Programme Definition

The research programme for a three-year period, currently 2003-2005, is based on the guidelines given by the Halden Board of Management, discussions in the Halden Programme Group, input and feedback from member organisations, and priority surveys. This process leads to a consolidated programme where enhanced safety and reliability of nuclear power systems remain the main objectives.

In formulating the programme plans, account is taken of the continuity, which is necessary to complete programme elements already commenced in previous periods. Long term activities and priorities are balanced with the requirement to develop short-term deliverables. An active programme must also be able to incorporate priorities as they develop and in this process also consider complementary work performed at other establishments and synergy emerging from interaction with non-nuclear environments. A continued interaction with and between the Project participants is therefore a fundamental part of the working out of the more detailed programme plans. Such interaction is considered essential for generating an integrated and as complete as possible understanding of safety issues of common interest.

Participating organisations' utilisation of the Project's facilities and capabilities on a bilateral basis is a necessary complement to the Joint Programme and creates an extended basis that is required to operate and maintain the facilities. The synergism between the jointly financed programmes and the bilateral contract activities also represents a most important vehicle for supporting the priorities of the different participating organisations in the Project.

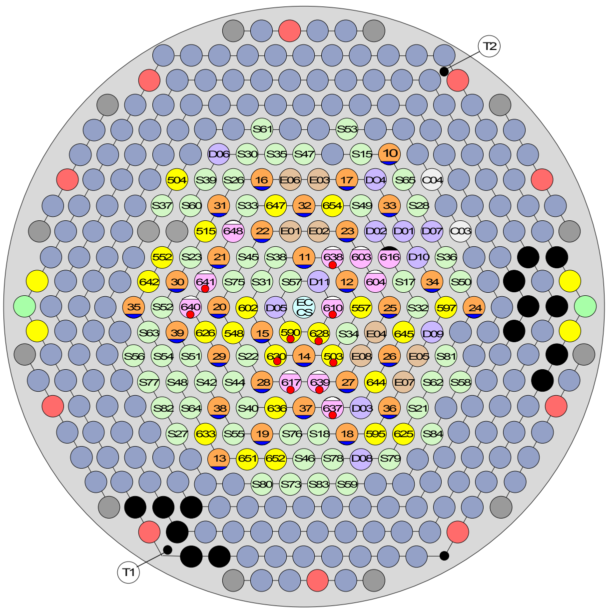

Figure 1. Cross-section of the Halden reactor core. Of more than 300 individually accessible positions, 100-110 in the central area are utilised for fuel elements. This increases the power density and protects the pressure vessel from radiation. 30-35 experiments can be served at the same time.

3. The Halden Reactor: A Versatile Tool for Irradiation Experiments

The main tool for the fuels and material research is the Halden Boiling Water Reactor (HBWR) with its range of experimental capabilities. The reactor, placed in a mountain cave in the middle of the town of Halden, is owned by the Institute for Energy Technology (IFE), which is also responsible for the legal liability, the safety, and the programme implementation. The licence for the reactor is valid until 2009, and preparations for a licence renewal application are already ongoing. The HBWR is a natural circulation boiling heavy water reactor using 14 tons of heavy water as coolant and moderator. The maximum thermal power is 25 MW, and the water temperature is 240°C, corresponding to an operating pressure of 33.3 bar. When in operation, steam is supplied to a nearby paper factory.

Figure 1 shows a cross section of the HBWR core. The circles are positions accessible through corresponding penetrations in the top lid. They can be used interchangeably for test rigs and standard HBWR driver fuel elements.

More than thirty-five instrumented fuel assemblies or irradiation rigs may be irradiated simultaneously in 300 core positions of which usually only the most central ones are being used to keep a slab of water between the core periphery and the reactor vessel, thus minimising irradiation induced embrittlement. The property changes of the vessel material are surveyed regularly with Charpy specimens, and the lifetime of the vessel is estimated to reach beyond 2030.

An Instrumented Test Assembly (IFA) represents a test rig in which a set of fuel rods or material specimens can be irradiated. In most cases the test rigs are designed such that fuel rods and specimens can be exchanged, thus facilitating a multipurpose and economical utilisation. The rigs are equipped with in-core instruments, which enable the quantitative assessment of fuel rod and material performance through in-reactor measurements under full power operation. They may also contain manipulators for moving measuring sensors or fuel rods, equipment for controlling the neutron flux level and axial distribution, and be built for PWR or BWR conditions to suit different test objectives.

About half of the test rigs are irradiated in LWR loops in which water reactor conditions are simulated. Fuels and materials to be tested are inserted into in-core pressure flasks connected to the light water circulation system. These systems, which are completely separated from the reactor cooling system, are designed for operation at pressures and temperatures of 165 bar and 340°C, respectively. An in-core pressure flask can be surrounded by high-enriched fuel rods in order to obtain neutron flux conditions typical of water reactors. As an example, the loop currently in use for PWR crud studies is illustrated in Figure 2.

The irradiation facilities and experimental rigs, supplemented by refabrication and instrumentation capabilities for irradiated fuels and in-core materials, provide the basis for a comprehensive fuels and materials testing programme. The main chapters and sections of the current programme in the Fuels & Materials area are as follows:

1. Fuel high burnup capabilities in normal operating conditions
- Performance of gadolinium fuel;
- Thermal and fission gas release behaviour of MOX fuel;
- Investigations on inert matrix fuel;
- Performance of WWER fuel;
- Power cycling behaviour of high burnup fuel;
- Fission gas release from fuel with high initial rating;
- Iodine release and gap inventory;
- Tolerable internal pressure in PWR and BWR rods;
- Cladding creep under variable loading conditions.

2. Fuel response to transients
- Rim fuel investigations;
- Loss of coolant studies;
- BWR power oscillations without scram;
- Axial gas transport in high burnup fuel.

3. Fuel reliability issues
- Cladding corrosion and hydriding
- CRUD deposition and axial offset effects;
- Localised corrosion.

4. Plant lifetime assessment
- Crack growth rate studies in PWR conditions;
- BWR crack growth rate test;
- Crack initiation (time to failure);
- Dry irradiation programmes;
- Out-of-pile CERT tests on irradiated materials;

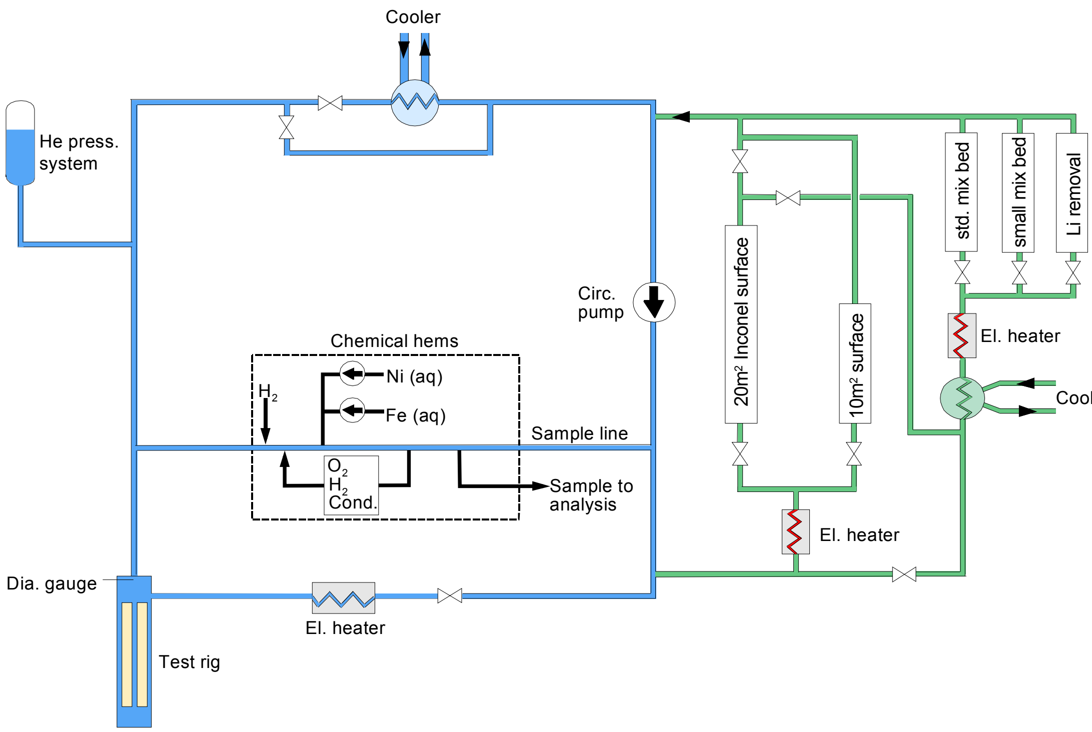

Figure 2. Schematics of a PWR loop for crud/AOA studies

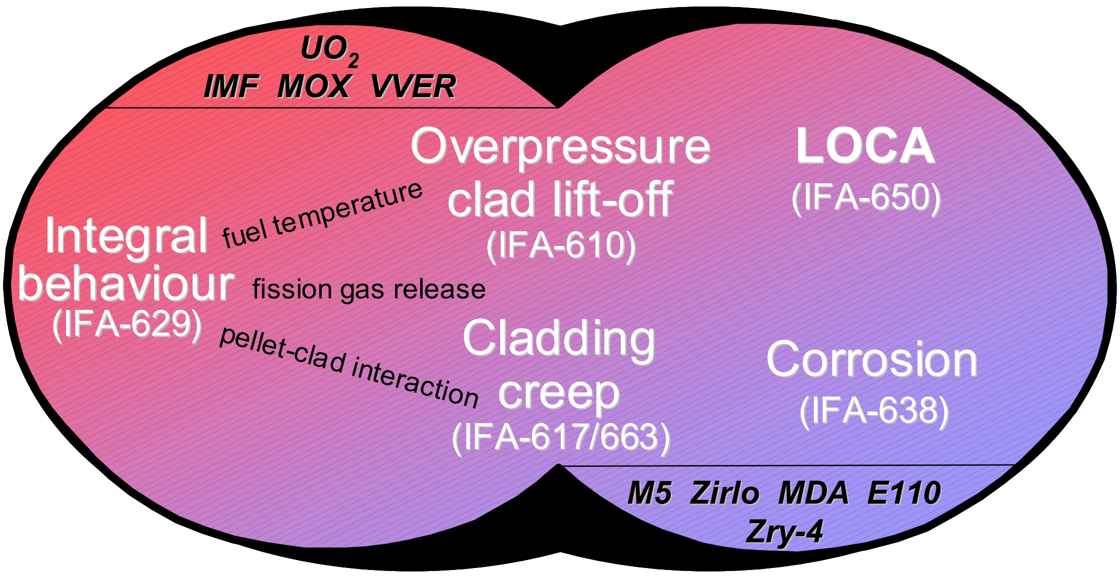

Figure 3. Through integral testing, different aspects of fuel performance are addressed in order to provide a more complete picture

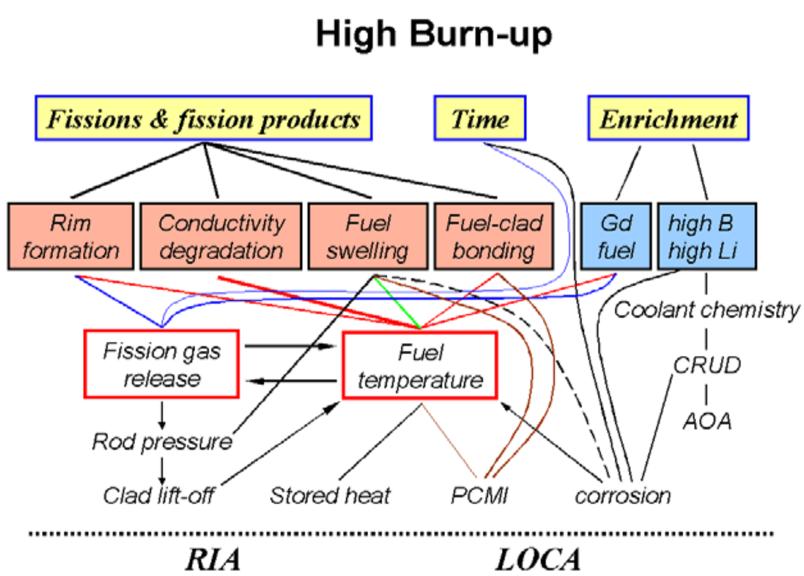

Figure 4. Interactions and dependencies of phenomena occurring in high burnup conditions

segments from commercial nuclear power stations. Related specific issues such as tolerable rod overpressure and cladding creep are studied in special experimental series, using the same or similar fuel and cladding types as in the integral studies. The corrosion experiment in turn utilises cladding materials also applied in the creep studies. And finally, sibling rods of the segments to be subjected to LOCA conditions are foreseen for both integral behaviour and overpressure studies.

4. Fuel Performance and Reliability, Extended and High Burnup

- Characterisation of IASCC test materials;
- Pressure vessel integrity studies.

Many of the issues addressed occur in combination with other issues and phenomena, and both fuels and materials behaviour must be viewed from different angles. Integrated testing is therefore essential to provide a picture that is as complete as possible. Figure 3 illustrates this principle, showing various fuel and cladding issues and how they are addressed in different experimental series belonging to different chapters of the programme.

The integral behaviour experiments address basic performance parameters such as fuel temperature (conductivity), fission gas release, and pellet-clad interaction using re-instrumented fuel

Fuel performance is in general the result of a complex interrelation of many different phenomena, and meaningful high burnup fuel behaviour studies have to deal with a number of requirements: as short as possible time for burnup accumulation, the demand on instrumentation to function reliably for the long time of in-core service, and the need for a separation of an increasing number of phenomena.

Figure 4 illustrates the main dependencies of (high burnup) phenomena occurring in normal operation conditions that need to be addressed in experimental programmes.

Instrumentation attached to fresh as well as pre-irradiated fuel and cladding is one of the main advantages of experimentation in the Halden reactor and indispensable in this complex situation. Reliable instrumentation has the advantage, unlike PIE alone, of giving insight how phenomena are linked with each other as they develop. Fuel performance experiments can be supported by the following instrumentation:

- Fuel thermocouples or expansion thermometers, which measure the fuel centreline temperature from which also conductivity degradation can be derived;
- Bellows pressure transducers, which provide data on fission gas release by measuring the rod inner pressure;
- Fuel stack elongation detectors, with which densification and swelling behaviour can be assessed;
- Cladding diameter gauge to determine radial deformations as function of power, holding time after ramping, and burnup;
- Cladding elongation detectors, which provide data on the onset and amount of pellet-cladding interaction, permanent deformation as well as relaxation capabilities of fuel and cladding as function of power and burnup.

The data mostly originate from re-instrumented fuel segments retrieved from commercial reactors, which allows investigating relevant states and phenomena, which occur after long in-core residence and associated high burnup. A fully developed capability for instrumenting pre-irradiated commercial fuel is available at Institutt for Energiteknikk's hot laboratory at Kjeller near Oslo. Regarding fuel performance, fuel centre thermocouples, rod inner pressure sensors and cladding elongation detectors are attached on a regular basis.

The results of fuels performance experiments can be used to:

- Provide data for fuel behaviour model development, verification and validation;
- Define starting conditions of transients and to assess the further developments;
- Show compliance of fuel performance with design, operational and safety criteria;
- Assess safety criteria with respect to available margins and reasonableness.

These objectives are valid for any level of burnup, but in recent years, investigations of the consequences of high burnup and extended fuel cycle schemes have dominated the Halden Project's fuels testing program. High burnup is, however, a moving target, and there is no single number that pinpoints this term in the various countries exploiting nuclear power on a commercial basis. Values range from 48 to 62 MWd/kgU depending on (LWR) reactor type, and numbers for MOX fuel are usually lower. The current and foreseen irradiation programme in the Halden reactor therefore also contains the high end of envisaged future burnup, and fuel burnups of 80-100 MWd/kg are included in certain experiments.

5. WWER-Specific Elements of the HRP Programme

WWER reactors are widespread in Eastern Europe, and several countries utilising this type of reactor are members of the Halden Reactor Project. These are Russia, the Czech Republic, Slovakia and Hungary, while Bulgaria intends to join in the near future. WWER reactor specific fuels, cladding materials and structural materials have therefore been included in the experimental programme since many years. Currently, the following ongoing or planned experiments contain WWER-related fuels and materials.

5.1. Irradiation of Standard and Modified WWER Fuel (IFA-503)

The 503 series of WWER fuels testing has been going on for many years and contains now the second loading irradiated since March 1999. The main objective is to study the behaviour of different modified WWER-440 fuel types in order to identify the fuel with optimal in-pile performance.

The Instrumentation includes fuel expansion thermometers, rod pressure sensors, and fuel stack elongation detectors. Irradiation started with fresh

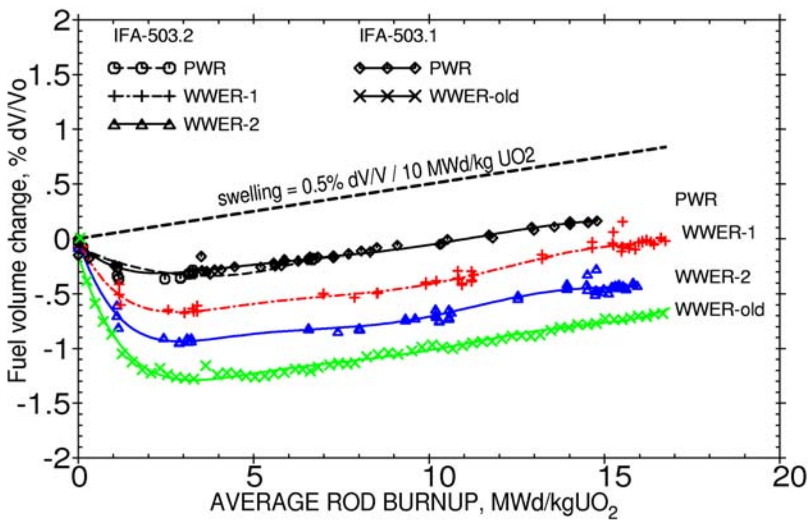

Figure 5. Densification and swelling behaviour of modified WWER fuel in comparison with old fuel types

fuel and is still going on, and the main attention was concentrated on fuel dimensional behaviour at BOL. Analysis has shown that the modified WWER fuels exhibit improved densification behaviour in comparison with the WWER fuel tested in the previous loading, IFA-503.1. Densification is monitored continuously during operation, and the development up to medium burnup is shown in Figure 5.

The least fuel densification was monitored in one of the modified WWER fuels, which was expected to be the best among the variants. The improvement of the WWER fuel densification is clearly seen in comparison with the reference PWR fuel tested in both loadings of IFA-503. Fuel swelling is about 0.5 vol.% per 10 MWd/kgUO_2 for all types.

The corresponding temperature measurements, Figure 6, show that WWER fuel temperature has become similar to the reference fuel. Both show stable thermal behaviour resulting from gap conductance improvement (gap closure) and fuel conductivity degradation.

The irradiation of the fuels will continue up to a burnup of 40-50 MWd/kgUO_2. During the further irradiation, it is planned to study the onset of fission gas release after power uprating.

A follow-on test of IFA-503 is already in preparation. This test will also include Gd-bearing WWER fuel in addition to further variants of modified fuel.

5.2. Corrosion Testing of Different Cladding Alloys (IFA-638)

The main objective of IFA-638 is to study the corrosion behavior of different zirconium based cladding materials up to high burnup. Cladding material were supplied by ENUSA, Framatome ANP, Kurchatov Institute, MHI and Westinghouse Atom AB. The experiment commenced in July 1998.

The rig contains fresh and pre-irradiated fuel segments as well as cladding material coupons. The operation conditions are given below:

- Water chemistry 3 ppm Li; 1000 ppm B (pH_{300}:7.1); 2-4 ppm H_2;
- ALHR 24-26 kW/m (upper 3 segments) 18-20 kW/m (lowermost segments);
- Coolant temperature 300-310°C (inlet); 310-320°C (outlet);
- Void fraction 0.2-0.5% upper three segments, 0.0-0.1% lowest segments.

The results are obtained from weight gain measurements of the coupons and oxide thickness measurements of the fuelled segments. Four interim inspections have been carried out so far for this purpose. The results shown in Figure 7 indicate that the performance of the Nb-bearing alloy E635 is equivalent to Zircalloy under PWR conditions.

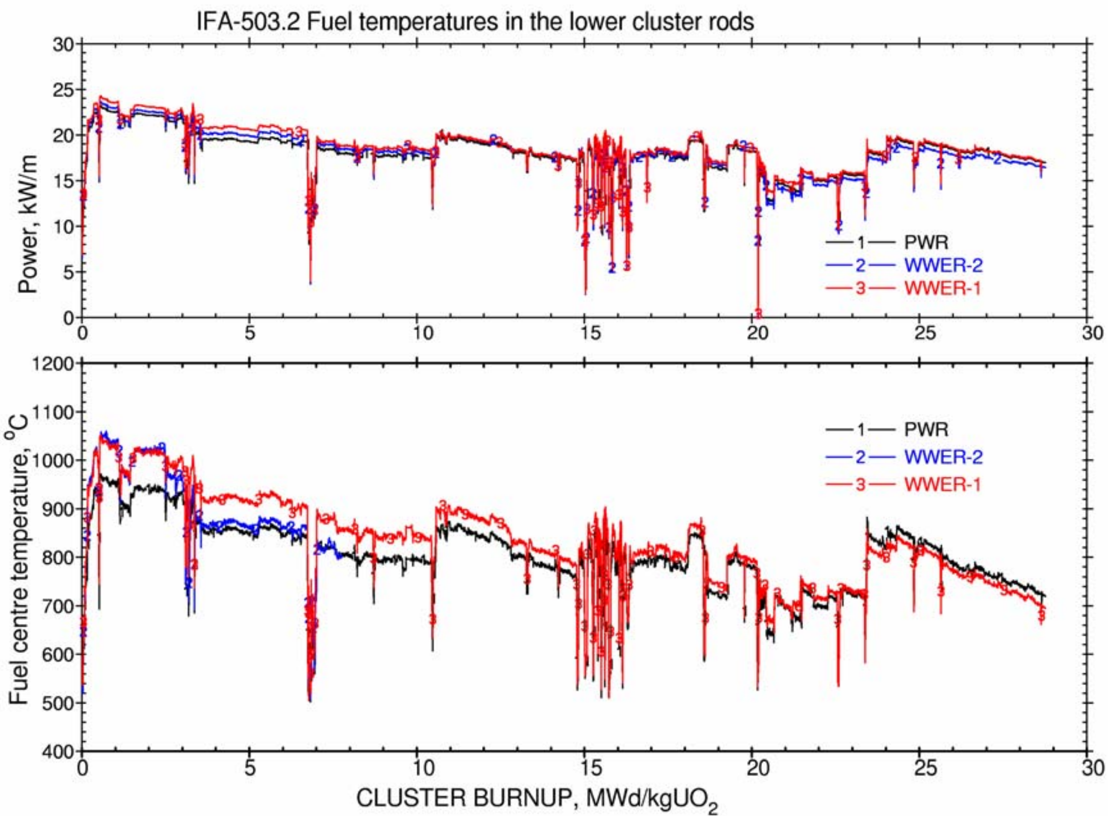

Figure 6. Development of fuel temperature in WWER and reference fuels

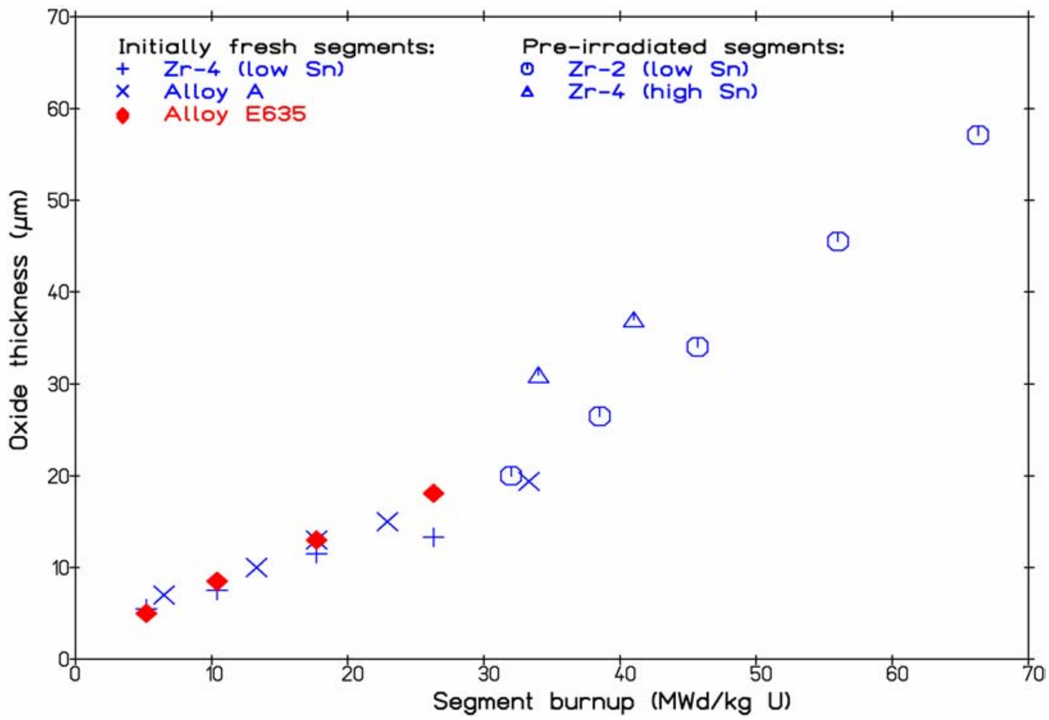

Figure 7. Oxide thickness growth of Alloy E635 under PWR conditions; comparison with Zry-2 and Zry-4 with low and high Sn content

WWER cladding is also contained in the creep test IFA-663. This test commenced in the Halden reactor not long ago, and meaningful results will only be obtained after more irradiation.

5.3. Future Experiments

The following experiments involving WWER fuel and cladding types are foreseen in the future programme of the Halden Reactor Project:

- Uprating of selected rods of the current loading IFA-503.2 in order to induce fission gas release;
- Loading of an IFA-503 successor. A new rig has been designed with room for six fuel rods and extensive instrumentation (measurement of temperature and rod pressure in all rods, fuel stack elongation, cladding elongation in three rods each);
- Utilisation of pre-irradiated segments (about 50 MWd/kgUO_2, Loviisa reactor) in the LOCA test series. It is also envisaged to employ sibling segments in the lift-off test series (IFA-610).

6. Acknowledgement

The results obtained from the experimental work at the Halden Reactor Project are due to the combined efforts of many staff members too numerous to mention. The supervision and evaluation of the WWER fuels performance test has for many years been in the hands of Boris Volkov, seconded from the Kurchatov Institute. His contribution is especially acknowledged. General thanks are extended to the Halden Project's member organisations and individuals therein for their continual support of this long-lasting international cooperation on reactor safety research and development.