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“Role of Halden Reactor Project for world-wide nuclear energy development”

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Abstract

The great interest for utilization of nuclear materials to produce energy in the middle of last century needed special investigations using first class research facilities. Common problems in the area of nuclear fuel development motivated the establishment of joint research efforts. The OECD Halden Reactor Project (HRP) is a good example of such a cooperative research effort, which has been performing for more than 50 years. During that time, the Halden Reactor evolved from a prototype heavy water reactor envisaged as a power source for different applications to a research reactor that is able to simulate in-core conditions of modern commercial power reactors. The adaptability of the Halden Reactor enables the HRP to be an important international test facility for nuclear fuels and materials development. The long-term international cooperation is based on the flexible HRP organizational structure which also provides the continued success. [1,2]

This paper gives a brief history of the Halden Reactor Project and its contribution to world-wide nuclear energy development. Recent expansion of the Project to the East and Asian countries may also assist and stimulate the development of a nuclear industry within these countries. The achievements of the HRP rely on the versatility of the research carried out in the reactor with reliable testing techniques and in-pile instrumentation. Diversification of scientific activity in the areas of development of alternative energy resources and man-machine technology also provide the HRP with a stable position as one of the leaders in the world scientific community. All of these aspects are described in this paper together with current experimental works, including the investigation of ULBA (Kazakhstan) production fuel in comparison with other world fuel suppliers, as well as other future and prospective plans of the Project.

Аннотация

Большой интерес к использованию ядерных материалов для производства энергии в середине прошлого столетия, потребовал специальных исследований с использованием первоклассного оборудования, а общие проблемы в области разработки ядерного топлива создали предпосылки для объединения исследовательских усилий. Халденовский Реакторный Проект (HRP), созданный под эгидой европейской Организации Экономического Сотрудничества и Развития (ОЭСР или OECD) является примером такой исследовательской кооперации, которая существует более 50 лет. В течении этого времени Халденовский реактор прошел путь от прототипа тяжеловодного реактора для различных применений до исследовательского реактора используемого для изучения поведения топлива и материалов современных энергетических реакторов. Адаптация к нуждам ядерной индустрии дала возможность HRP стать важной международной исследовательской базой для разработки новых видов топлива и материалов. Долговременное международное сотрудничество основано на гибкой организационной структуре, которая также обеспечила успех при проведении исследований. [1,2].

Данный доклад кратко представляет историю HRP и его вклад в мировое развитие атомной энергетики. Последние расширения Проекта за счет участия стран Восточной Европы и Азии может также способствовать развитию ядерной индустрии в этих странах. Достижения HRP основаны на многосторонних исследованиях, проводимых на реакторе с использованием надежного испытательного оборудования и внутриреакторных детекторов. Диверсификация научной деятельности в области альтернативных источников энергии и технологии организации взаимодействия человека и машины (МТО), также обеспечивают устойчивую позицию HRP как одного из лидеров мирового научного сообщества. Все эти аспекты деятельности кратко описаны в представленном докладе вместе с результатами по текущим экспериментальным работам, включая исследование топлива, произведенного в Казахстане Ульбинским Металлургическим Заводом, в сравнении с топливом других мировых поставщиков, а также будущие и перспективные планы HRP.

Paper to be presented in the VI International Scientific Workshop “Contemporary issues of uranium industry”, Almaty, Kazakhstan, September, 14-16

1. Introduction

The safe and reliable operation of nuclear power plants benefits from R&D advances and related technical solutions. The OECD Halden Reactor Project is a leader in these advances with research programs devised to provide answers in a direct and effective manner. The Project is operated by the Norwegian Institute for Energy Technology (IFE) under the auspices of the OECD Nuclear Energy Agency and its strong international profile and solid technical basis represent an asset for the nuclear community at a time in which maintaining centers of expertise is becoming increasingly important.

The Halden Reactor Project (HRP) is a joint undertaking of more than 100 organizations from eighteen countries that together finance the experimental programs of the Project. Collaborations with East-European and Asia countries in support of plant safety and reliability are also expanding.

2. A brief history of the Halden Reactor Project

In the beginning of the 1950's there was a general trend towards the civil use of nuclear energy. In Norway, the Institutt for Atomenergi was established in 1948 with the plan to build a prototype nuclear reactor and then to establish a Norwegian nuclear industry. In 1955, the Parliament agreed a budget for building the Halden Reactor and as enriched uranium was only available to a few nations, it was initially designed to operate with natural, metallic uranium.

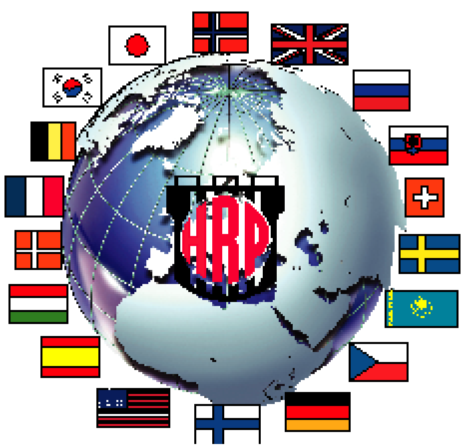

Figure 1. Flags of the country members of the HRP and view of the reactor hall of the Halden Reactor.

Building a prototype reactor being an expensive undertaking, it soon became apparent that Norway needed partners for such an endeavor and the Project was opened to those countries interested in the commercial utilization of nuclear technology. The Halden Reactor Project was thus formed, under the auspices of the then OECC (nowadays OECD) and the first research program was signed by 12 countries in 1958, including Norway. The research program of the Halden Reactor started with the reactor reaching criticality in 1959. By this time, it was possible to obtain enriched uranium on a commercial basis and the second core loading of the reactor in 1962 consisted of enriched uranium. This allowed the reactor power density to be increased to that expected for commercially operating power reactors.

From the beginning, emphasis was placed on in-core instrumentation to allow for monitoring of the behavior of reactor fuel under various conditions. This approach, along with the ability to perform several tests simultaneously, was seen as vital to the reactor's ability to produce meaningful research results. Later, the research also changed character from the more fundamental problems of nuclear science to the more technical aspects of nuclear reactor technology. These technical aspects came to include issues related to control room operation not only those related to fuel and materials behavior.

In the 1970's, Norway's opposition to nuclear power was growing and this, together with oil finds in the North Sea, effectively put a stop to domestic plans for nuclear power. Out of this situation came the driving force for the Halden Reactor Project to start research into control room systems in order for it to take part in the development of the Norwegian North Sea oil industry. Since Norway no longer had any ambitions to build its own nuclear industry, the institute was renamed "Institutt for energiteknikk" (IFE). The scope of research was also broadened to include all energy related technologies. During the 1980's, a new research strategy was pursued in parallel to the original: Man Technology Organization (MTO) activities were added to secure interest from Norwegian industries. In the 1990's, IFE increased its direct connections with the nuclear industry, enabling IFE's experience in reactor research safety and reliability to be of direct benefit to, for example, utilities. From this position, IFE started to play an important role in the Norwegian assistance program to the Russian nuclear power plants on the Kola Peninsula.

International interest in the Halden Reactor Project continued to grow, reflected in the number of member countries. In the middle of the 1990's, the East European countries of Czech Republic, Slovakia, Hungary and Russia became associated to the HRP. In 2008, the Project continued to expand with the associated membership of Kazakhstan (see *Fig. 2*). Other countries have also expressed a wish or intention to be a member, including China, India and Mexico, and individual organizations continue to join as associated members such as most recently, the Department of Energy in the USA.

Another important trend over the years has been an increase in the number of bilateral projects carried out utilizing the Halden Reactor, carried out in parallel to but separate from the HRP research program, adding to the overall benefit provided by IFE to the global nuclear industry.

Figure 2. Signing of the agreement between the HRP and ULBA Metallurgical plant in Halden in 2008.

3. Key features of the Halden Reactor Project

The key features of the HRP are: a fast response to nuclear industry demands; production of results with practical applicability for fuel licensing and certification; maintenance of an upgraded facility and qualified personal; and application of innovative research technologies. The research carried out for the participating countries is jointly financed by the members and is carried out in a series of 3-year programs known as the “Joint Programme”. This is regarded in many countries as a strategic program for the testing of fuel and reactor components and the organizations participating in the HRP represent a complete cross section of the nuclear community including licensing and regulatory bodies, vendors, NPP utilities and research organizations. The Joint Programme is designed to generate key information for safety and licensing assessments and aims at providing:

- Basic data on how fuel performs in commercial reactors, under normal and transient operation, and accident conditions, with emphasis on extended fuel utilization.
- Knowledge of plant materials behavior under the combined deteriorating effects of water chemistry and nuclear environment for ageing and degradation issues.

The Halden Reactor is a heavy water moderated and cooled reactor which operates at a maximum thermal power of 20 MW. The reactor and its main circuits are inspected by independent authorities and the IAEA, and there is a solid technical basis for reactor operation well beyond 2030 [1]. More than 30 fuel or materials tests can be carried out simultaneously in the Halden Reactor, including within light water loops used for providing coolant conditions representative of different types of NPP. The in-reactor experiments are supported by a modern technical infrastructure including mechanical and electronic workshops, chemistry laboratories and a computerized data handling system. Fuel production, irradiated fuel rod re-fabrication and instrumentation as well as post irradiation examinations are also performed at the IFE hot laboratory at Kjeller. All technologies and products developed as part of the HRP Joint Programme are available to participants, who also have access to Halden facilities and expertise for their own development work.

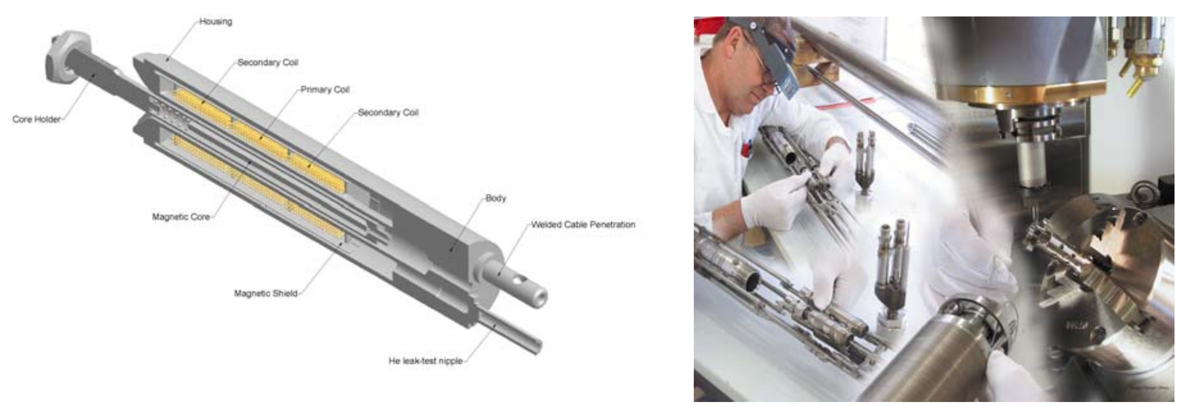

Figure 3. A key feature of the Halden tests is reliable in-pile instrumentation.

4. Diversification of IFE and HRP's Activities

In the beginning of the 1980's, it was recognized that reactor research should not be solely concentrated on research reactors. Other aspects of commercial reactor operation were of equal importance, such as computer technology, human factors and psychology. To date, these new areas in Man-Technology-Organization (MTO) represent 40% of the Project's activities and include areas such as: operator procedures; computerized surveillance; visualization techniques; use of virtual reality; advanced communications; software reliability; and human reliability in power station environments.

Central to these activities has been the construction and operation of the Halden Man-Machine Laboratory (HAMMLAB), which is now regarded as a reference facility for human factor studies and for advice on control room engineering. It has provided the basis for studies on the performance of control room operators in complex and automated environments. Advances in technology and increased need for access to research simulators led to HAMMLAB being upgraded. Currently, the systems that can be simulated include a French PWR, a Swedish BWR and a Russian VVER as well as an off-shore oil production rig.

A more recent field of interest has been the development of graphical interfaces and the application of Virtual Reality (VR) technology. This builds on previous work on computer based interfaces and led to the construction of a VR Laboratory in 1996. VR has proven to be an excellent tool for rapid, interactive, high quality design of control rooms. Tools to assist in verification and validation of such designs have been developed as well as tools for maintenance training.

Finally, Computerized Operation Support Systems (COSSs) are also developed and evaluated. These systems are designed to assist operation and maintenance through fault detection, diagnosis and planning of operations. These systems cover: alarm handling; signal validation; transient detection; computerized procedures; graphic interfaces; and core surveillance.

The MTO activities benefit from regular confrontation with practical implementation of real life requirements in power plants and in process industry. This continuous scrutiny levied by all participants on the Project's experimental results and conclusions is particularly beneficial in preventing the insularity that often characterizes research projects [2,5].

Figure 4. The Halden Man-Machine Laboratory (HAMMLAB) and VR lab in operation.

5. Main achievements of the HRP in the area of the nuclear fuel and material development for commercial NPPs

The “standard” UO_2 fuel pellets for Light Water Reactors (LWR), developed by many fuel vendors during many years, have to date provided excellent performance in most reactor operation conditions. However, in order to achieve even higher fuel reliability, further investigations are needed aimed at development of optimal design and fuel microstructure.

In the 1980’s, fuel performance was studied with an emphasis on in-pile fuel stability (densification and swelling) to avoid cladding collapse as well as hard PCMI (pellet-cladding-mechanical-interaction) during the initial stages of operation. Many in-pile tests in the Halden Reactor were performed in order to find an optimal fuel microstructure, fuel-pellet size and form, acceptable fuel-to-cladding gap size and internal gas pressure for different types of NPP. Primary fuel properties were also investigated like fuel thermal conductivity, gap conductance and specific capacity. Different variants of Zr-based cladding materials were also tested to ensure compatibility with the different UO_2 fuel pellets.

Since economic aspects have started to play a more important role for fuel utilization in commercial NPPs, a detailed understanding of the fuel properties at high burn-up have been required. Investigations at Halden thus also include: the formation of high burn-up structure (HBS) at the pellet rim; thermal conductivity degradation; fuel and cladding creep rate and mechanical properties; fission gas release (FGR); and PCMI during steady-state and transient conditions. The data generated by these studies are invaluable for development and verification of various fuel performance codes, which are used to determine operational margins of LWR fuel to high burn-up. Some special aspects of high burn-up fuel behavior (fuel relocation) under Loss of Coolant Accident (LOCA) conditions have also been investigated by the HRP.

Some of the significant investigations by the HRP to support fuel and material development for commercial NPPs are shown in *Figs 5-9*.

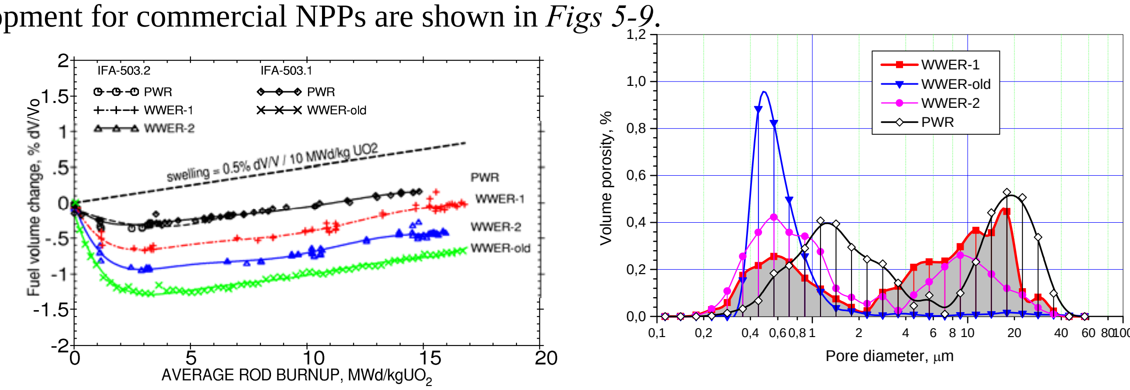

Figure 5. Fuel densification and swelling as a function of burn-up and microstructure.

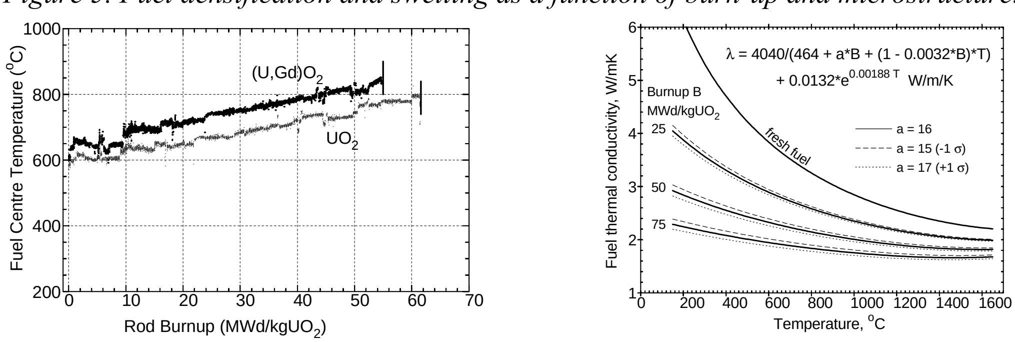

Figure 6. Study of fuel thermal conductivity and its degradation as a function of burn-up.

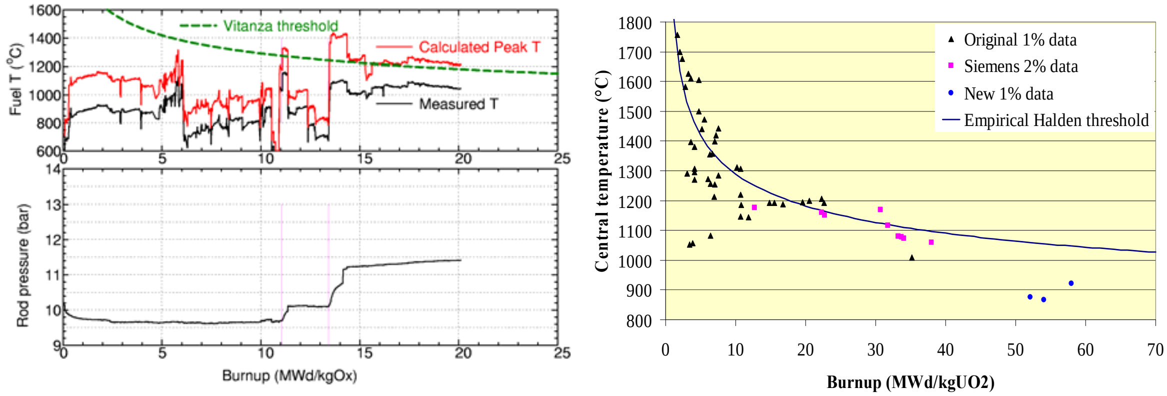

Figure 7. Halden fission gas release temperature threshold as a function of fuel burn-up.

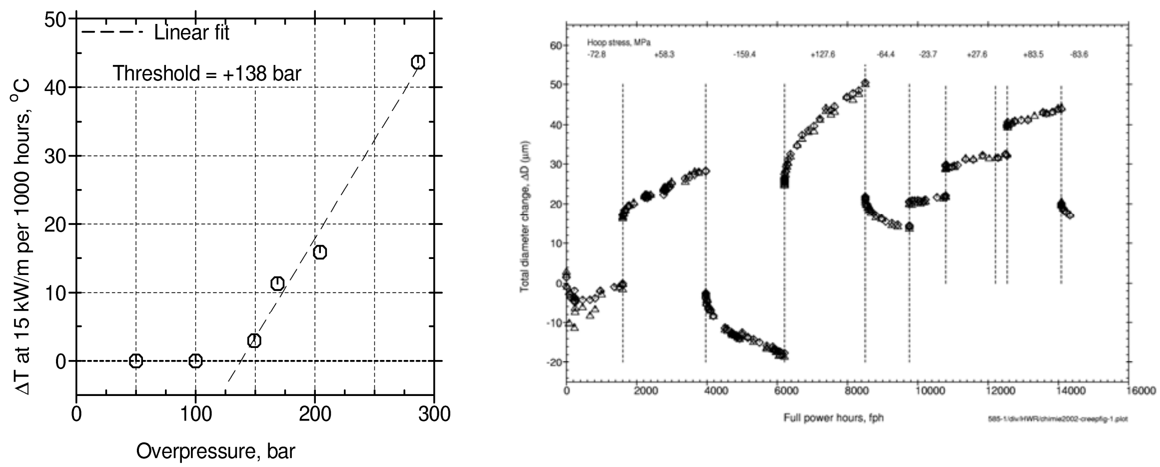

Figure 8. Overpressure test and cladding creep determined during in-pile tests in the Halden Reactor.

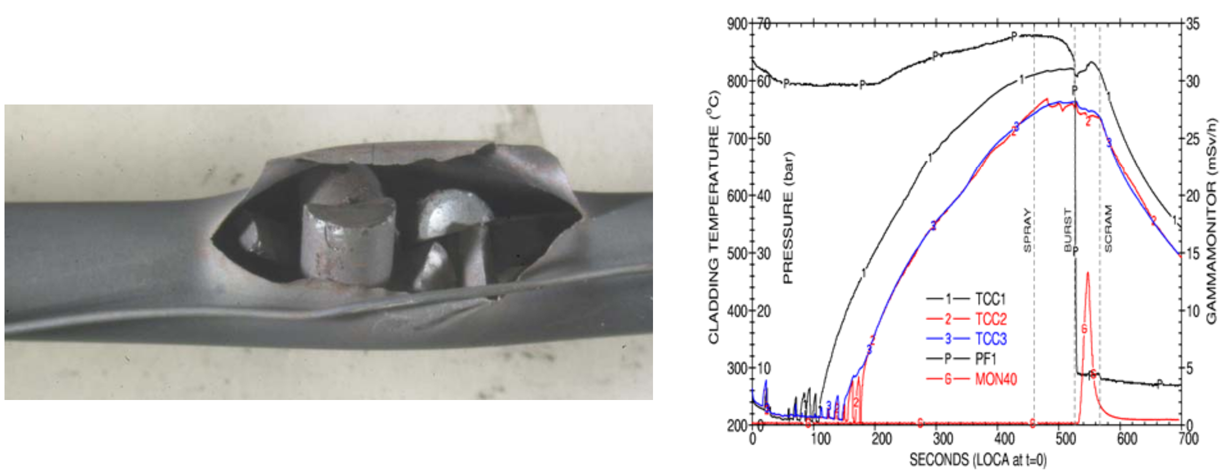

Figure 9. Tests in the Halden Reactor performed to investigate high burn-up fuel relocation during LOCA.

6. Current R&D activity of the HRP and future plans

Despite public ambivalence to nuclear energy, recent advances in nuclear technology that have increased safety and reliability of nuclear fuel utilization have led to a nuclear renaissance in the 21st century. Progress in the nuclear area around the world has also demanded specific investigations oriented to the prolongation of NPPs and the modification of ‘standard’ fuels and claddings. The most important aim in this development is to achieve as high as possible fuel burn-up concurrent with safe and reliable operation. Recently, the most important investigations in the Halden Reactor, proposed by HRP member organizations, cover the problems of suppressing FGR from fuel and increasing the corrosion resistance of fuel claddings. Both these issues can directly limited fuel burn-up and reduce effectiveness of NPPs.

In order to resolve FGR problems it is proposed to increase grain size of the fuel pellet with some specific additives facilitating this process. Another option is to enhance fuel thermal conductivity and decrease operational temperature which most influences FGR. A comparative test, with different fuels supplied by AREVA (France) and ULBA (Kazakhstan), is currently being carried out in the Halden Reactor. The test matrix, given in the table below, also includes uranium-beryllium fuel of ULBA production.

Manufacturer	AREVA	AREVA	ULBA	ULBA	AREVA	AREVA
Fuel type	Doped	Standard UO2	UO2/BeO	Active Sintered	Large Grain	Doped
Density[g/cm3]	10.50	10.55	9.75	10.68	10.48	10.53
Cr2O3 Content[ppm]	1580	N/A	N/A	N/A	N/A	1050
Grain size [μm]	70	11	9	45	55	59
Pellet shape	Dished	Dished	No Dishing	No Dishing	Dished	Dished

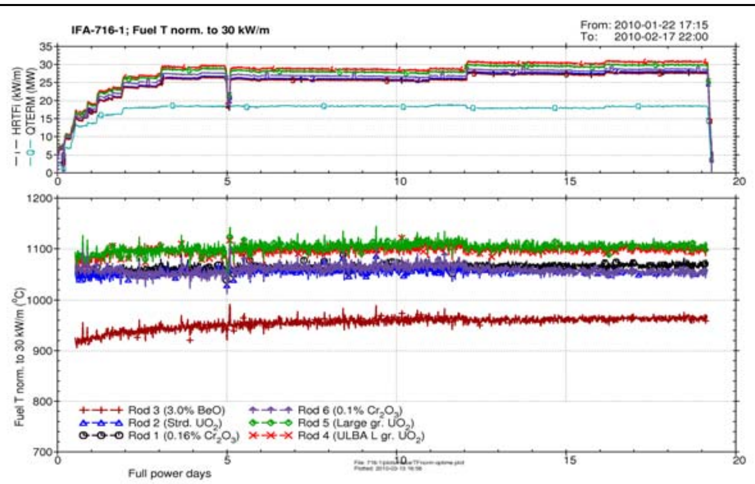

Figure 10. First results of ULBA fuel (large grain UO_2 and BeO fuel) investigation in the Halden Reactor.

The results of the in-pile measurements shown in *Fig. 10* for the first irradiation period confirmed that the fuel temperatures measured in the different large grain and ‘standard’ fuels are similar whereas that measured in UO_2-BeO fuel (ULBA) is lower due to better thermal conductivity. The test will continue for several years, aimed at finding a reasonable solution for FGR.

A test aimed at studying corrosion resistance of cladding materials with different alloying elements is also one of the important investigations in the current HRP Joint Programme.

A future plan of the HRP is to participate in the research program for Generation IV reactors by studying new materials and by developing new in-pile instrumentation.

7. Conclusion

This paper briefly introduced the Halden Reactor Project and its contribution to world-wide nuclear energy development. A brief history of the establishment of the HRP also gave a picture of the Project as an international research center. The success of the HRP activities rely on the versatility of the research carried out in the reactor with reliable testing techniques and in-pile instrumentation. The results obtained in Halden are a basis for fuel and material certification for introduction in commercial reactors. Diversification of HRP scientific activity in the areas of man-machine technology also provides the HRP with a stable position as one of the leaders in the world scientific community. Recent investigations proposed by HRP member-organizations and fuel vendors like AREVA, Wesinghouse, TVEL and ULBA may promote and stimulate some innovative world wide fuel production for new NPPs.

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