The Halden Reactor Project: Experience gained in international research*

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Abstract. The Norwegian government has with the successful completion of the June 2006 "Symposium and Technical Workshop on Minimisation of Highly Enriched Uranium (HEU) in the Civilian Nuclear Sector" confirmed its engagement for minimizing the risk related to the continued use of fissile material in general and HEU in particular. One suggested concept in reducing risk associated with fissile material required for research is the concentration of research efforts in shared facilities. The increased global demand for nuclear energy also points towards the need for first class research facilities. Pooling resources makes sense as a way to maximise research efforts. But how should a shared facility work and function?

The OECD-Halden Reactor Project (HRP) is a good example of operation of a shared research facility which has been in operation for nearly 50 years. During that time the HRP has evolved from a prototype heavy water reactor envisaged as a power source for maritime surface vessel propulsion to a research reactor able to replicate the in-core conditions of most of the worlds types of power reactor. Thus making the HRP an important international test facility within the nuclear industry.

This evolution was not possible without the international cooperation which was present from the start. The flexibility of the organizational structure has also proven vital to the continued success of the Project. This paper gives a brief history of the Halden Reactor Project as well as the hosting company, Institutt for energiteknikk (IFE), as the success of the one is reliant on the other.

The success of the Project and the Institute is largely reliant on the versatility of both the reactor design and also the organizational structure. Both are described in this paper. Finally a summary of the keys to success is given which can be used as a template for other international research projects.

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1. Introduction

First a look at the historical perspective: The initial idea in the 50's for the building of the Halden Reactor was that Norway wanted experience in building nuclear reactors for use in ship propulsion. It soon became clear that Norway could not afford this project alone, even the close cooperation between Norway and the Netherlands was not enough to complete the project. Finally in 1958 when the reactor was opened the project had become international with the Institute for Atom Energy (Now called Institute for Energy Technology) being the host.

Then as now the research was organised in 3 year programmes. Countries participating provide financial support, and are part of the steering committee which decides on the content of the research. Visiting research scientists are also sent to Halden to gain experience and to participate in the operation of the experiments. Which and how many countries are members may change. There is no obligation to re-join after a 3 year period has finished. This flexibility is probably one of the main reasons that this organisation form has remained unaltered in now almost 50 years. It has also meant that the research program is constantly changing so as to be as up to date as possible.

Although this paper is concerned with describing the factors for success of the Halden Reactor Project [1] the role of the hosting institute needs also to be described. The Institutt for energiteknikk (Institute for Energy Technology, IFE) is Norway's largest international research institution. The Institute is a non-profit organization with government appointed board of directors and is charged with supporting energy related industries in Norway. IFE's five areas of research currently are: nuclear technology and physics; nuclear safety and reliability; petroleum; energy and environment; and safe interaction between man, technology and organisation.

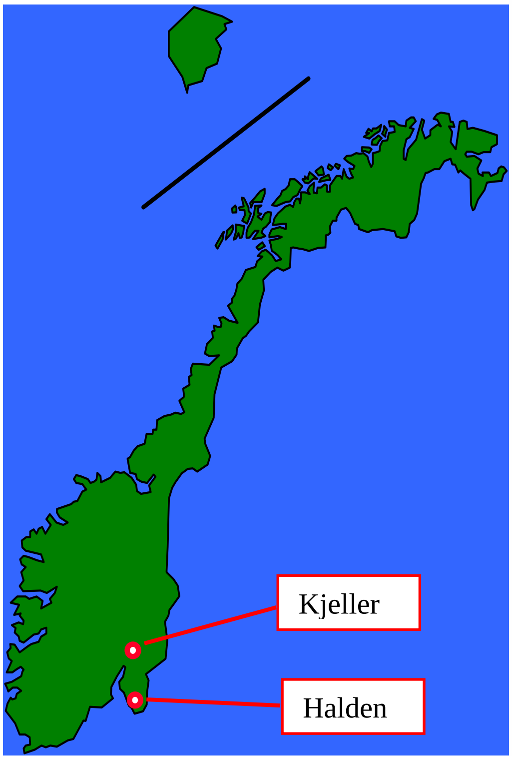
IFE has facilities at both Kjeller, located near Norway's capital Oslo, and Halden, located on the south eastern border to Sweden *(Fig 1)*. IFE has ca. 550 employees, roughly equally divided between Kjeller and Halden, and a turnover of about 60 Million Euros.

1.1. Motivation for writing this paper

Norway's address to the IAEA's 49th general conference signalized a new effort in nuclear security [2]. As part of this the reduction of the use of HEU in the civil nuclear sector was highlighted as an important step towards better security. As part of their strategy the Norwegian government organized the "Symposium and Technical Workshop on Minimisation of Highly Enriched Uranium in the Civilian Nuclear Sector", which was held in Oslo, June 2006 [3]. Thus confirming its engagement for minimizing the risk related to the continued use of fissile material in general and HEU in particular.

Another risk associated with use of fissile material is from diversion for theft. This is recognized as a problem for small as well as large facilities. Therefore, it is proposed that nuclear security can be improved by pooling research, resulting in fewer locations for sensitive materials. The best benefits of this are achieved when facilities are shared on an international, or regional bases. These benefits also include a reduced cost to the individual member countries and, we argue, a higher quality of the research conducted.

Thus the Norwegian Government encourages the formation of regional research centres. How this can be achieved is a very difficult and complex issue. Here we wish simply to give as an example how international collaboration has led to the success of the Halden Reactor Project. A Project which has been of great benefit to the hosting nation, Norway, as well as providing leading international research for the member countries [4].



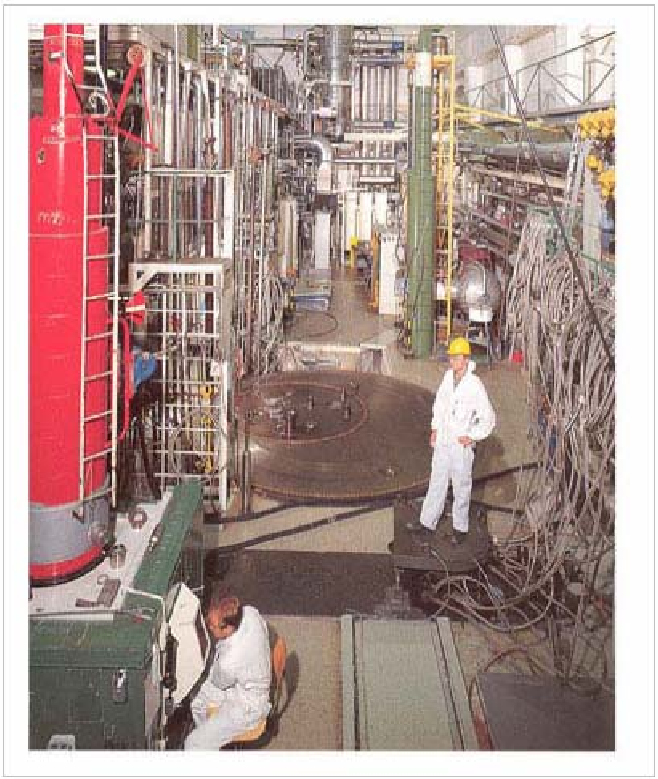


FIG. 1.IFE's facilities in Norway (red circles), and Inside the reactor hall at Halden.

2. A brief history of the Halden Reactor Project (HRP) and the Institutt for energiteknikk (IFE) [5]

Before we start the history of the Halden Project detailing the when and how, it is important to relate why it all began. During the 50's there was a general optimizm regarding the civil use of nuclear technology. This saw the establishment in Norway of IFA (Institutt for Atomenergi) already in 1948. Then with the help of the Netherlands, which provided the necessary uranium, and with Norway's own heavy water the research reactor JEEP-1 was set in operation in 1951.

Later President Eisenhower's 'Atoms for Peace' speech at the UN in 1953 added to this optimizm and IFA started plans to build a prototype power reactor. This formed part of Norway's plans to establish its own nuclear industry, and in 1955 the Parliament agreed a budget for building the Halden reactor. The previous bi-lateral partnership with the Netherlands was no longer in existence as they had secured a deal with the USA for purchasing their own materials testing reactor. As the building of a test reactor was expensive it soon became apparent that Norway needed a new partner.

As enriched uranium was only available for a few nations, the Halden Reactor was initially designed to operate with natural metallic uranium. This made it an interesting project from an international perspective as it opened for many countries the possibility for commercially exploitable reactor technology. So after some negotiation the Halden Project was formed under the auspices of the OECC (nowadays OECD). The first research programme was set to last three years and was signed by 12 countries including Norway on July 1, 1958.

2.1. Early beginnings

From 1958 to 1968 the main emphasis of the research at Halden was to gain the necessary experience to develop a nuclear generating industry, also in Norway. The building of the Halden reactor was central to this research which saw the reactor first go critical June 29 1959. By the time the first 3 year research programme was completed there existed the ability to obtain enriched uranium on a more commercial basis. So the second fuel loading, in 1962, existed of enriched uranium allowing the reactor power density to be increased to that expected for a commercially operating power reactor.

From the beginning emphasis was placed on in core instrumentation to allow the monitoring of the behaviour of reactor fuel under various conditions. By the end of the first 10 years of operation it became apparent that this in core instrumentation, along with the ability to run several tests simultaneously, was vital to the reactors ability to produce meaningful research. The research also changed character from the more fundamental problems of nuclear science to the more technical aspects of power reactor operation.

These technical aspects were also to include problems outside of the core. So starting in 1967 the research programme was to include not only fuel and materials testing but also problems related to control room operation.

2.2. From atoms to energy

In the 70's Norway's own interests in nuclear power dwindled. This was not apparent in the beginning as in 1971 IFA created the company Scandpower which was seen being an engineering company capable of designing nuclear power stations. But opposition against nuclear power was growing, this combined with the oil finds in the North Sea effectively put a stop to domestic plans for nuclear power. Finally in 1979 the Norwegian parliament declared that nuclear power was not an option for the foreseeable future.

However, this did not mean the end of IFA and the Halden Project. In fact IFA had been at work establishing links to industry thanks to the research into control room systems. This enabled IFA to take part in the development of Norwegian North Sea oil exploitation.

As Norway no longer had any ambitions to become player in the nuclear technology world, IFA's role needed to change. In 1980 the institute was given a new name, IFE (Institutt for energiteknikk), and new statutes. Atoms were exchanged for energy and the scope of the research was broadened to general energy related technologies.

The future for the Halden Reactor was also uncertain, but continued international support helped to secure its existence. Also the establishment of HAMMLAB (Halden Man Machine Laboratory) provided the Project and the Institute with more than just a research reactor.

2.3. Research reactor to Reactor Research

During the 80's a new strategy for activities at Halden emerged. Two approaches were to be pursued in parallel. First the Halden Reactor should be used to maintain the international interest through the Halden Project. Second the MTO (Man Technology Organization) activities should secure interest within the Norwegian industries.

By the end of the 80's the existence of the Halden reactor again was under question, leading up to a proposal in the Norwegian parliament to close the reactor after 1993. IFE met this threat by first increasing direct activities with industry as well as indicating that IFE's experience in reactor safety could be of direct benefit to Norway. Thus IFE was provided an important role in the Norwegian assistance programme to the Russian NPPs in the Kola peninsula.

The international interest in the Halden Project continued to grow with the number of member countries doubling. Another trend was an increase in the number of bi-lateral research contracts. This provided another source of income to pay for reactor operations. This combined with the creation of several spin-off companies secured IFE's and the Reactor's existence at least for the foreseeable future.

2.4. Future prospects

With the renewed interest in nuclear power, IFE and the HRP are in a strong position to provide the nuclear industry with first class research facilities and expertise. The HRP has also recognised the need to educate the next generation of nuclear engineers, bringing a new role to an ever changing Project.

3. Versatility of reactor design

Another factor contributing to the project's success is the design of the reactor. The Halden reactor is a boiling heavy water reactor typically operated at 235 °C. The neutron flux level is typical of commercial power reactors. What makes the Halden Reactor unique is a combination of instrumentation, availability and versatility.

With two operational periods each year a typical availability of 50% is achieved. This combined with many experimental positions more than compensates for the moderate flux level. In-pile instrumentation has been under development since the start of the reactor in 1958. To date almost all physical parameters can be measured; fuel temperature, stack elongation; cladding outer temperature, diameter; rod internal pressure, to name but a few *(Fig 2 & Fig 3)*.

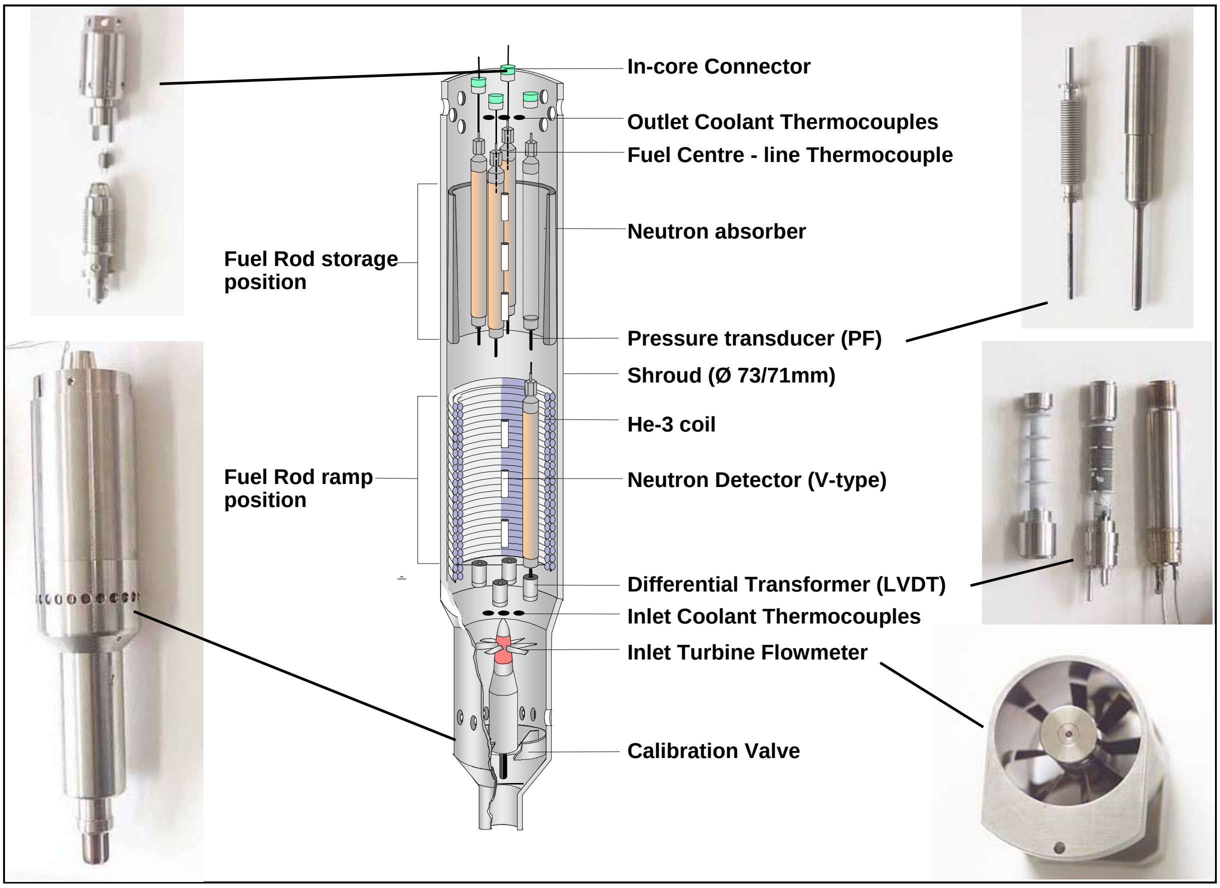


FIG. 2. Example of instrumentation available for a fuel power ramp test assembly in the Halden Reactor.

The present day complement of experimental assemblies range in complexity from rudimentary, non-instrumented rod bundles to some of the most integrated and complex in-reactor tests ever designed. In the fuel and materials area, tests done in the HBWR are representative of actual commercial reactor conditions.

In-core instrumentation has been developed at Halden from the very beginning. Emphasis has always been placed on measuring changes in physical properties of fuel and materials whilst they are in actual reactor conditions. Now, after 50 years of development the list of available measuring techniques is extensive. Ranging from calometric determination of channel power, as well as SPNDs (self powered neutron detectors) to the in-core measurements of fuel temperature (centreline or pellet periphery), internal rod pressure and fuel stack elongation. These have all helped in the study of fuel behaviour, enabling the determination of the exact point for fission gas release, or clad lift off and even fuel densification and swelling.

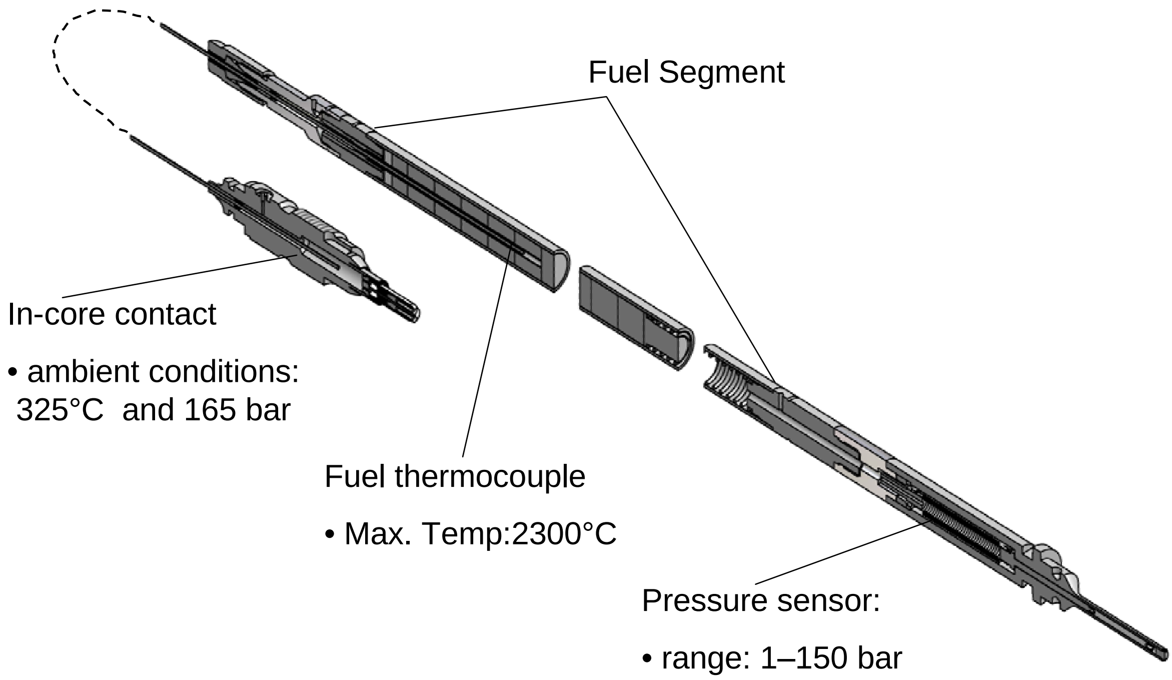


FIG. 3. Cut out view of re-instrumented fuel rod showing placement of fuel centre thermocouple and internal rod pressure sensor.

Instruments are not restricted just to fuel; the clad and other material properties can also be studied on-line. These include clad outer diameter, clad elongation and fuel clad gap size. Here, it should also be mentioned the extensive research programme into irradiation assisted stress corrosion cracking (IASCC) with the specialized crack growth rigs *(Fig 4)*.

Test assemblies do not just exist in the reactor; they also need to be constructed as well as analysed afterwards. IFE has also developed its own manufacturing capability from simple fuel manufacture to re-instrumentation of pre-irradiated fuel. PIE analysis is also frequently performed at IFE ranging from visual inspection and gamma scanning to more advanced techniques of analysing fission gas released or radial gamma scanning of fuel pellets to name but a few.

The versatility of the reactor is also important; several different conditions can be simulated simultaneously: BWR, PWR, PHWR. All with their own unique water chemistry, temperature and pressure. Power ramps can be performed for individual fuel channels without affecting the whole reactor; and recently a LOCA test was performed in realistic conditions, *(Fig 5 & Fig 6)*.

This instrumentation has enabled research into many different topics. The topics currently covered are divided into fuel and materials research. For the fuel research increased burn up and transient behaviour are being investigated. Whilst for the materials research plant life time assessment is the topic of interest.

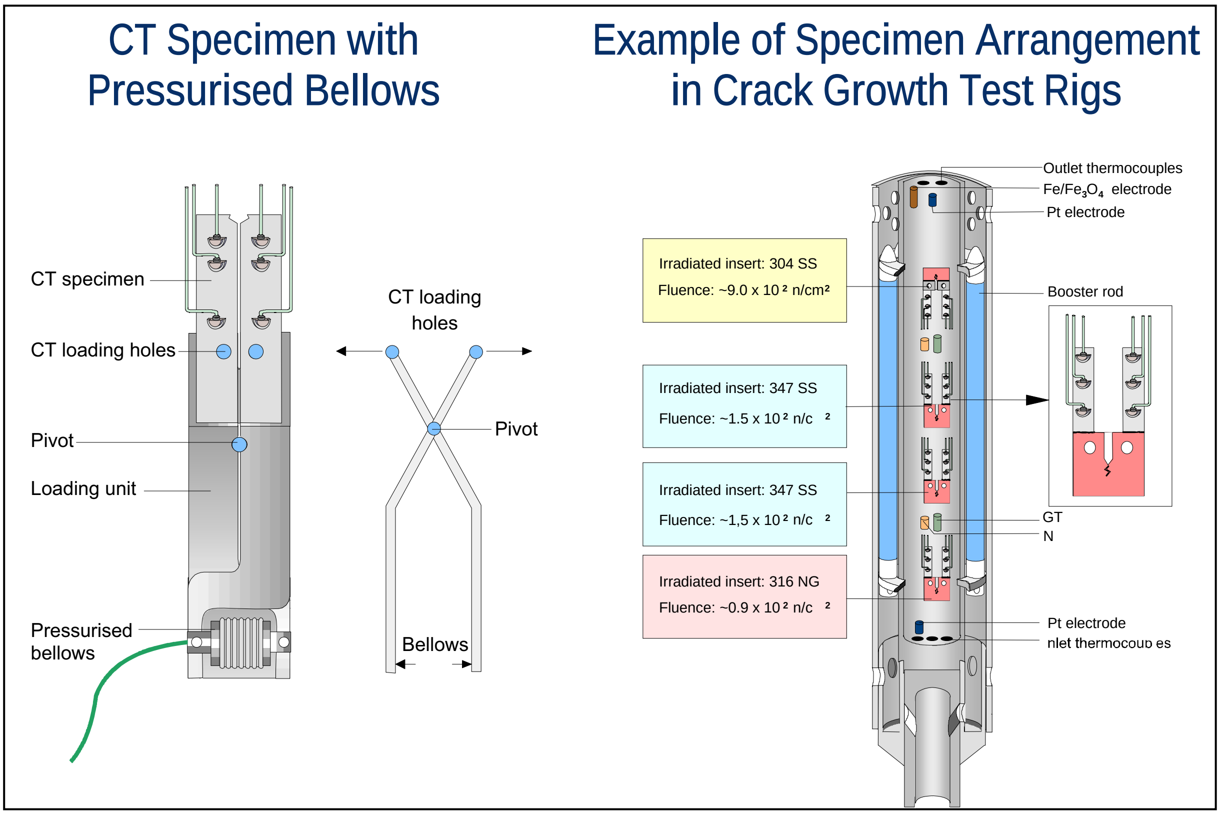


FIG. 4. Example of IASCC test rig. Crack growth is measured on-line with varying radiation levels, water chemistry and stress.

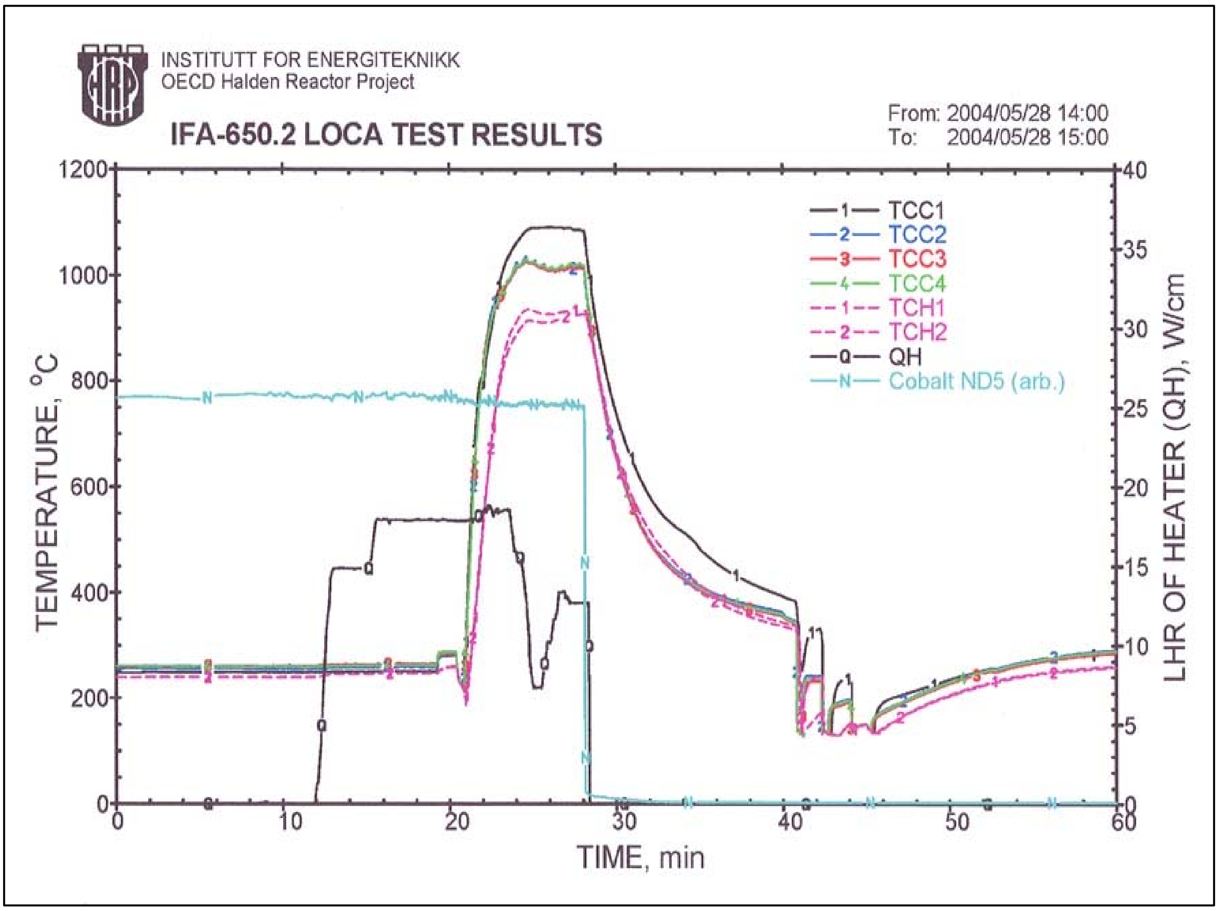


FIG. 5. Temperature measurements from LOCA test assembly.

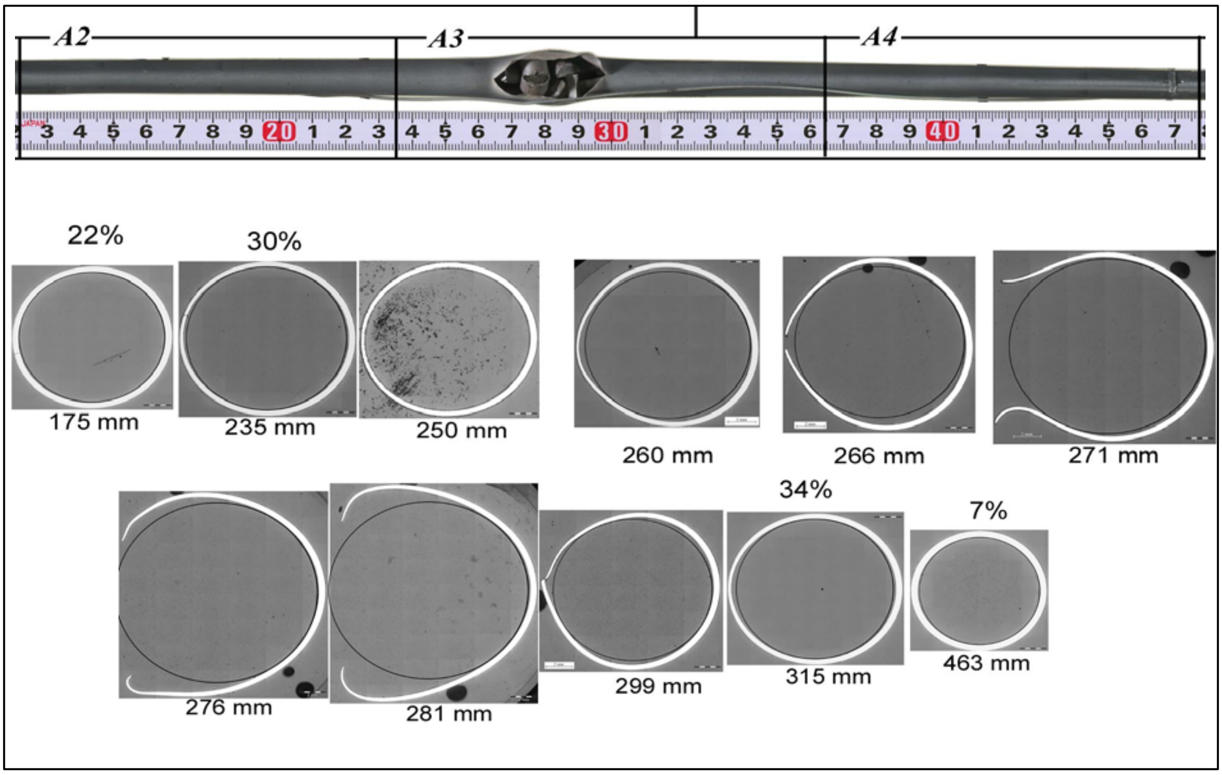


FIG. 6. Picture of clad burst with accompanying cross sections for a LOCA test.

4. Outside the core (MTO)

In the beginning of the 80’s it was recognised 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. This is where the dynamic nature of the Halden Project’s organisation proved its usefulness, with an increased emphasis being placed on these new areas in the 1982-84 three year programme. To date these new areas in Man-Technology-Organisation (MTO) represent 40% of the Project’s activities and include areas such as: operator procedures, computerised surveillance, visualisation 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) *(Fig 7)*. HAMMLAB is now regarded as a reference facility for human factor studies and for advises 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 the decision to establish an upgraded version HAMMLAB. This mainly addresses the needs of the nuclear and the oil/gas industry. Currently simulated systems include a French PWR, a Swedish BWR and a westernised VVER as well as an off-shore oil production rig.

FIG. 7. Halden Man-Machine Laboratory (HAMMLAB) in operation.

A more recent field of interest for the HRP/IFE has been the development of graphical interfaces and the application of Virtual Reality (VR) technology *(Fig 8)*. This is building 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, Computerised Operation Support Systems (COSSs) are also developed and evaluated as part of the HRP. 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, Computerised procedures, Graphic interfaces and Core Surveillance.

The man-machine systems activities benefit from regular confrontations with practical implementation of real life requirements in power plants and in process industry. This continuous scrutiny levied by all participants of the Project's experimental results and conclusions is particularly beneficial in preventing the insularity that often characterizes research projects.

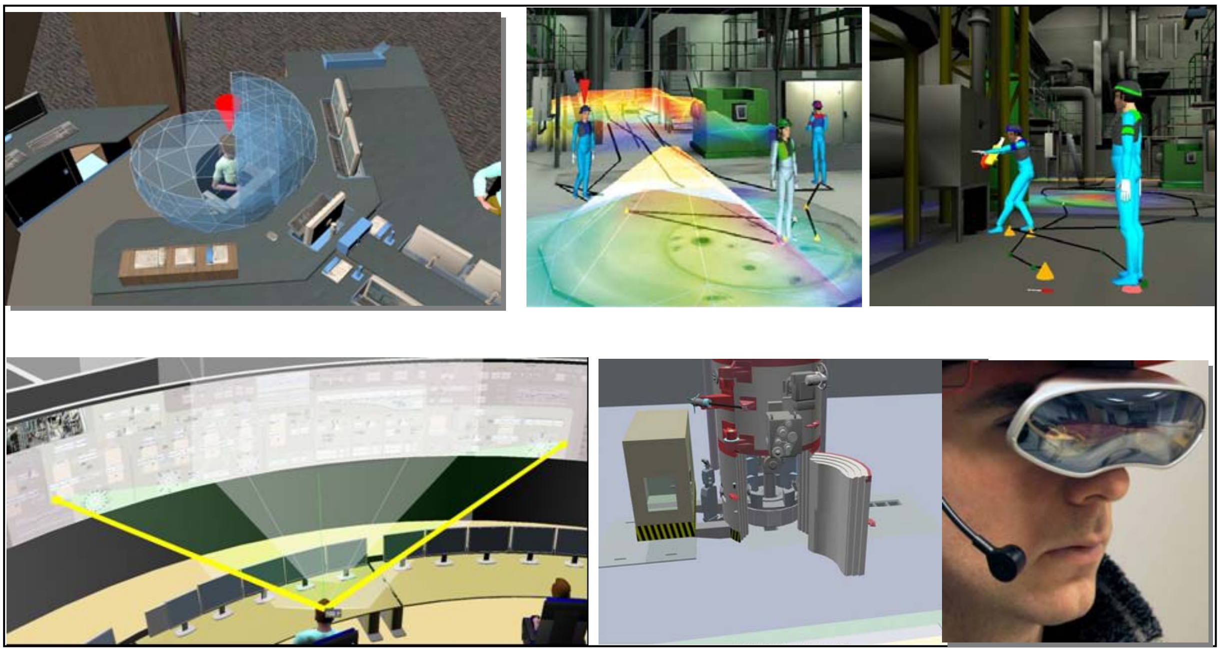


FIG. 8. Examples of uses of Virtual Reality.

5. Versatility of organizational structure

As mentioned before the Halden Reactor Project (HRP) does not exist on its own but is hosted by the Institutt for energiteknikk (IFE). This dipolar existence allows research results to be directly used in commercial applications as well as drawing on industrial experience as a research source.

The Halden Project acts in a way as a customer for conducting research from IFE. This research is performed under what is called the joint programme. Membership of the Project then, in turn, gives access to these results. More importantly the members decide on the contents of the research programme and decide which direction the project will take. Members also benefit from the possibility to use the facilities for bilateral research. The cost of this research can often be greatly reduced by combining bi-lateral and joint programme experiments.

One of the other benefits to member organizations is the ability to second staff to Halden. This is typically to follow up a particular experiment of interest or to learn more about a specific area of research. Over the years more then 300 scientists have been seconded to the Project, typically for a period of one to three years. Nowadays this arrangement is mainly offered to young scientists, reflecting a new educational role of the Project.

The results from the Project are available in a variety of different ways. The basic form is the data file cataloguing instrument readings from the various experimental assemblies in the reactor. This allows member organizations to perform their own analysis of the experimental data. The Project also provides the results in the more digestible form of work reports. This forms the Projects own report series the whole of which is available to all members.

One of the aims of the Project is to provide a forum for discussion. The main facilitator for this is the Enlarged Halden Programme Group meetings (EHPGs) which are held twice every 3 year period. These meetings provide an opportunity to present the latest research results as well as hearing presentations from other organizations. Due to the variety of topics covered under the Joint Research Programme these meetings provide a unique opportunity for people from the different sectors of the nuclear industry to meet.

The Project also organizes many workshops for more specialist topics and has started a series of international summer schools aimed at educating young scientist.

5.1. Single owner: many members

The relationships between the Project (HRP) and the Institute (IFE) are not made any easier to understand by the inclusion of the OECD/NEA. This we will attempt to explain here. First the legal owner of the reactor is the Institute with the Project acting as a research customer. However the Project has a great deal of autonomy compared with other commercial activities. This autonomy is executed by the Halden Board of Management (HBM) and the Halden Program Group (HPG), one group for fuel and materials (F&M) and one for Man-Technology-Organization (MTO). Each group consists of one representative from each member country. They meet separately twice a year, with the HBM giving general and long term goals and the HPG dealing with more technical aspects of the Joint Research Programme.

Here it must be stressed that the HRP only has responsibility for the content of the research programme. IFE has sole responsibility for its execution, including the security and safety of the nuclear and non-nuclear facilities.

The HRP is the first and longest lasting international project under the auspices of the OECD/ Nuclear Energy Agency (NEA). The role of the OECD/NEA is to encourage and promote the broadest possible participation in the Project by its Member countries, to co-ordinate the Project's work with other activities in the relevant fields and to provide legal assistance where required.

Currently there are 17 member country members, representing over 100 organizations *(Fig 9)*. They represent a complete cross section of the nuclear industry, including national research organizations, reactor and fuel vendors, utility companies and the licensing and regulatory interests.

FIG. 9. Flags of the current HRP member states.

5.2. Flexible membership

There is no obligation to renew membership and membership has varied, see *Fig 10*. This ensures that the research topics are relevant and not too specialized for the needs of one organization. However, it is also possible for organizations to order specific research from IFE. These so called bi-lateral research accounts for half of the activates at Halden.

Period	'58-'61	'61-'62	'64-'66	'67-'69	'70-'72	'73-'75	'76-'78	'79-'81	'82-'84	'85-'87	'88-'90	'91-'93	'94-'96	'97-'99	'00-'02	'03-'05	'06-'08
Total	12	14	11	12	8	9	9	11	10	10	9	14	18	20	18	18	17
Norway	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Euratom*	6	6															
Austria	x	x	x	x				x									
Belgum												x	x	x	x	x	x
Denmark	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Finland		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
France													x	x	x	x	x
Germany			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Italy			x	x	x	x	x	x	x	x	x	x	x	x			
Netherlands			x	x	x	x	x	x	x	x		a	a	a			
Sweden	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Switzerland	x	x	x	x								x	x	x	x	x	x
U.K.	x	x	x	x				x	x	x	x	x	x	x	x	x	x
U.S.A.		x	x	x			x	x	x	x	x	x	x	x	x	x	x
Japan				x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spain												x	x	x	x	x	x
Korea														x	x	x	x
Argentinia															a		
Brazil						a								a			
Bulgaria																a	
Czech												a	a	a	a	a	a
Hungary													a	a	a	a	a
Russia													a	a	a	a	a
Slovakia													a	a	a	a	a

x Signatory Members   a Associated Members

FIG. 10. Member countries for project periods 1959-2008.
** Euratom is counted as 6 countries.*

Membership is not only restricted to countries with nuclear industries. Denmark, despite closing down its last research reactor in 2000, is still a member of the Project due to interest in the research Man-Technology and Organization (MTO). Research which as mentioned is also applicable for non-nuclear industries.

Membership is not even restricted to OECD member countries. The project currently has four countries, Czech republic, Hungary, Russia and Slovakia, which are associate members from outside the OECD countries.

5.3. Bi lateral contracts

In addition to the joint programme work, a number of organizations in the participating countries execute their own development work in collaboration with the Project. These bilateral or multi-lateral arrangements constitute an important complement to the joint programme and normally address issues of commercial interest to a participant organization or group of organizations.

These bi-lateral activities have proven to be essential for the development of the research programme. Not only have they provide additional funds to share the cost of operating the reactor and other facilities, but they also provide needed input from industry regarding the relevance and applicability of the research. This is especially prevalent for the MTO research where the practical application of research is the primary goal.

5.4. Intellectual property rights

In addition to providing training, experience and countless amounts of experimental data for the projects member countries, the Halden Project has also been extremely beneficial for the hosting country Norway. Despite the fact that the Norwegian nuclear industry did not materialise there have been several benefits for conventional Norwegian industry (in particularly petroleum) and has lead to several commercialisation successes; the most recent being in electronic energy trading and cable fault detection. In addition the Institute provides commercial services based on the reactor and associated technology with turnover comparable to the research project.

The program results are systematically reported in Work Reports and in conferences organised by he Project. Special workshops with participation of experts are frequently arranged for in-depth assessments of specific issues, especially when new programme topics are to the established.

6. Summary

The Halden Reactor has evolved considerably from its initial goal, which was to demonstrate the heavy water concept with a modest thermocouple and turbine flow test. The reactor facilities have been progressively updated and, through a series of innovative techniques, the system has now become one of the worlds most versatile test reactors.

This development has been possible largely due to the flexibility of the organizational structure. Thus we believe that the Halden Project is a good example of how to operate an international research project. The key ingredients can be summarized as:

- Division of research programme contents and its execution.
- Political and financial independence.
- Flexible project membership and active participation of project members.
- Constantly evolving research programme.
- Backing of a broader international organization.

This structure has enabled the HRP to maintain a position as a leading research organization within a wide spectrum of areas. The continued international support is just one measure of the importance of the Project to the member countries, and many of the expertises required to execute the Project has been directly applied to Norwegian industry.

In short the separation of the programme contents of the HRP and the execution of research by IFE has proven a success for both the international partners and the host nation. The pooling of international research efforts has saved the member countries considerable costs and helped to enrich their own research efforts.

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