Safety research at the OECD Halden Reactor Project

Brief history: Halden & the Halden Project
HRP Organization and Members
HRP Facilities and Work areas
Examples of results

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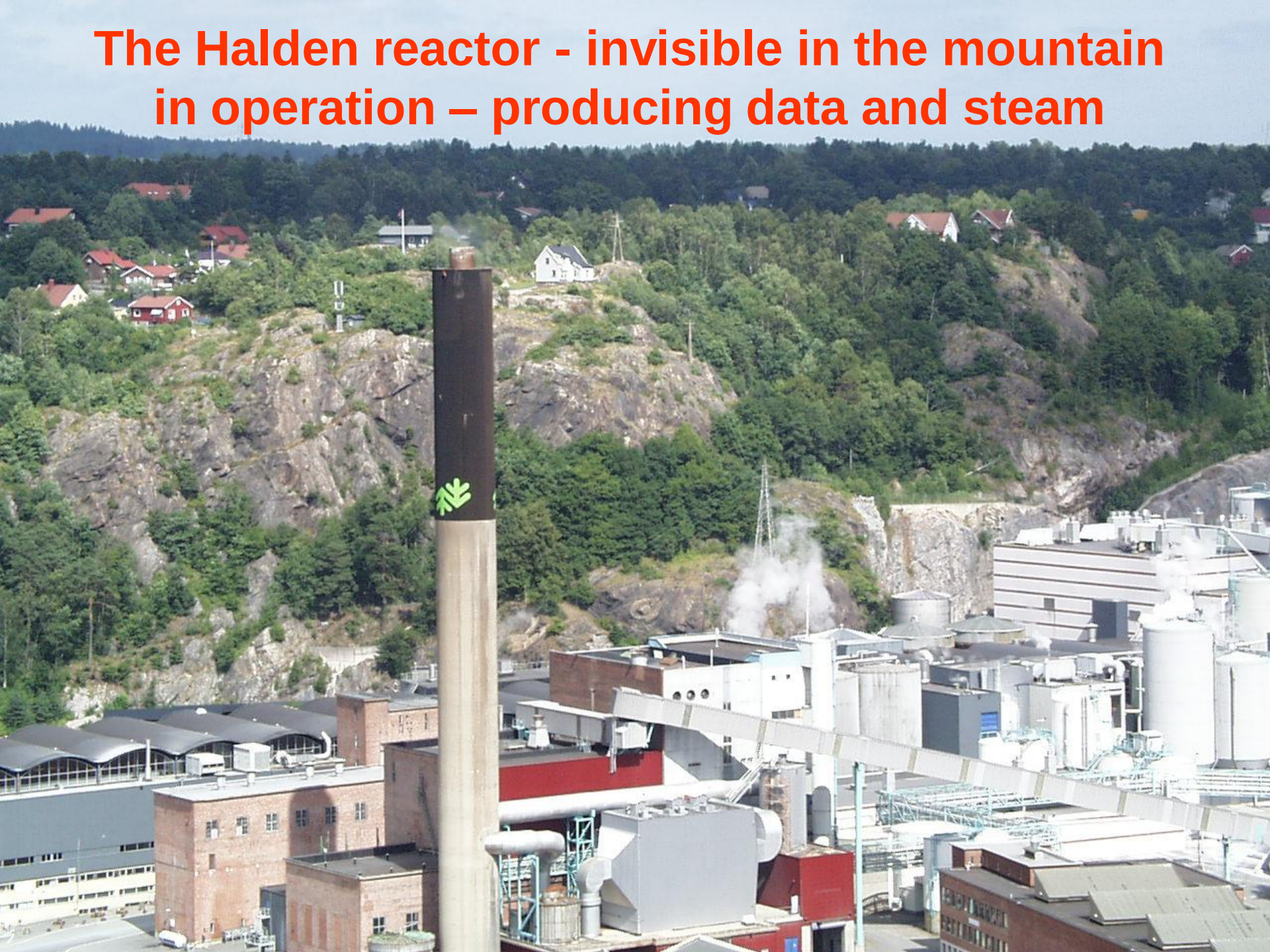
Forskningsseminarium Reaktorsäkerhet, Aronsborg 22-23 April 2010

Halden – located in south east corner of Norway

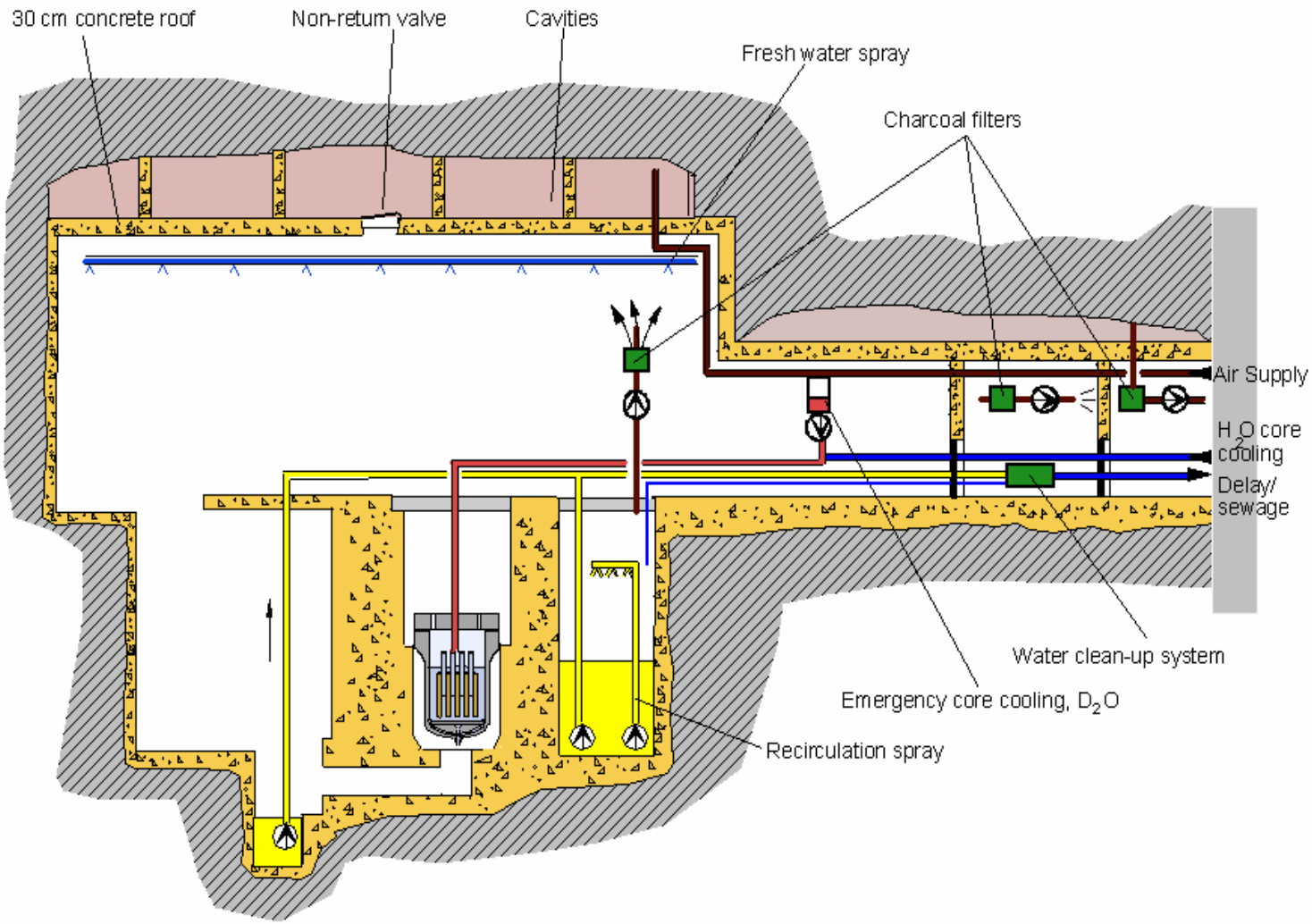
Halden – Norway's Gateway to Europe

Halden & the Halden Reactor site

The Halden reactor - invisible in the mountain in operation – producing data and steam



HBWR is located in a mountain cave – went critical 29.06.1959



OECD Halden Reactor Project

- International collaborative research for Safe and Reliable Operation of Nuclear Power Plants
  - affiliated to OECD NEA in Paris
  - located in Halden, Norway
  - operated by Institute For Energy-technology, IFE
- Halden Agreement first signed in 1958
  - Renewed every 3rd year
  - Current program period from 2009 to 2011
    - (2008: Reached 50 years :>))
  - OECD countries, through a Signatory organization, signs the Halden Agreement
  - Associated Party Agreement (APA)
    - an extension to the original Halden Agreement to allow for multiple independent organizations in a country, or non-OECD countries, to participate to the HRP
- HRP is jointly funded by its members:
  - 18 countries
  - > 100 nuclear organizations world wide
- Participant types
  - Utilities, Vendors, Licensing Authorities and R&D centers

HRP Members – Signatories and Associated Parties

Signatory members:

- **Norway** – **IFE** - Institutt for energiteknikk
- **Belgium** - **SCK/CEN** - Belgian Nuclear Research Centre
- **Denmark** - **Risø DTU**
- **Finland** - **MITI** - Finnish Ministry of Trade and Industry, operated by **VTT**
- **France** - **EDF** - Electricité de France
- **Germany** – **GRS** - Gesellschaft für Anlagen- und Reaktorsicherheit mbH
- **Japan** - **JNES** - Japan Nuclear Energy Safety Organization
- **Korea** - **KAERI** - Korean Atomic Energy Research Institute
- **Spain** - **CIEMAT** - Spanish Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
- **Sweden** - **SSM** - Swedish Radiation Safety Authority
- **Switzerland** - **HSK** - Swiss Federal Nuclear Safety Inspectorate
- **UK** - **NNL** – National Nuclear Laboratory
- **USA** - **US NRC** - United States Nuclear Regulatory Commission

Associated Parties:

- **USA**
  - **GE** - Global Nuclear Fuel
  - **Westinghouse** Electric Power Company (WEC-LLC)
  - **EPRI -** Electric Power Research Inst.
- **Japan**
  - **JAEA, CRIEPI, Mitsubishi NP** and **11 utilities**
- **France**
  - **IRSN** - French Institut de Radioprotection et de Sûreté Nucléaire
- **Czech Rep.** - **NRI -** Czech Nuclear Research Institute
- **Slovakia** - Slovakian **VUJE** - Nuclear Power Plant Research Institute
- **Hungary** - Hungarian Academy of Sciences, **KFKI** Atomic Energy Res. Inst.
- **Russia** - "**TVEL**" JSC.
  - Research Centre "Kurchatov Institute",
  - Research Institute VNIIAES
- **Kazakhstan** – **Ulba** Manufacturing company

Other Swedish Bilateral partners
- Studsvik Nuclear
- KSU Studsvik

Swedisk HRP consortitium
- Vattenfall bränsle
- OKG AB, Forsmark KG AB, Ringhals AB
- Westinghouse Sweden

Possible new members to the HRP-
work in progress

- **US Department of Energy (DOE)**
  - long standing contacts through DOE labs
  - APA offered in spring 2009, on hold due to budget situation
  - INL would take the lead with more labs taking part –
  - **APA to be signed in April 2010**
- **India**
  - APA candidate, consortium: NPCIL, AERB and BARC
  - contact through OECD NEA, offer sent in January 2010
  - **received positive statement in early March 2010**
- **Mexico**
  - Signatory candidate, offer sent September 2009
- **China**
  - APA candidate, consortium: CNPEC and CNPRI)
  - APA offered in January 2010
- **AREVA, France**
  - APA candidate, offer sent in January 2010

Work areas of the Halden Project

Halden MTO research areas:

Human performance

Human System Interfaces

Operation Support

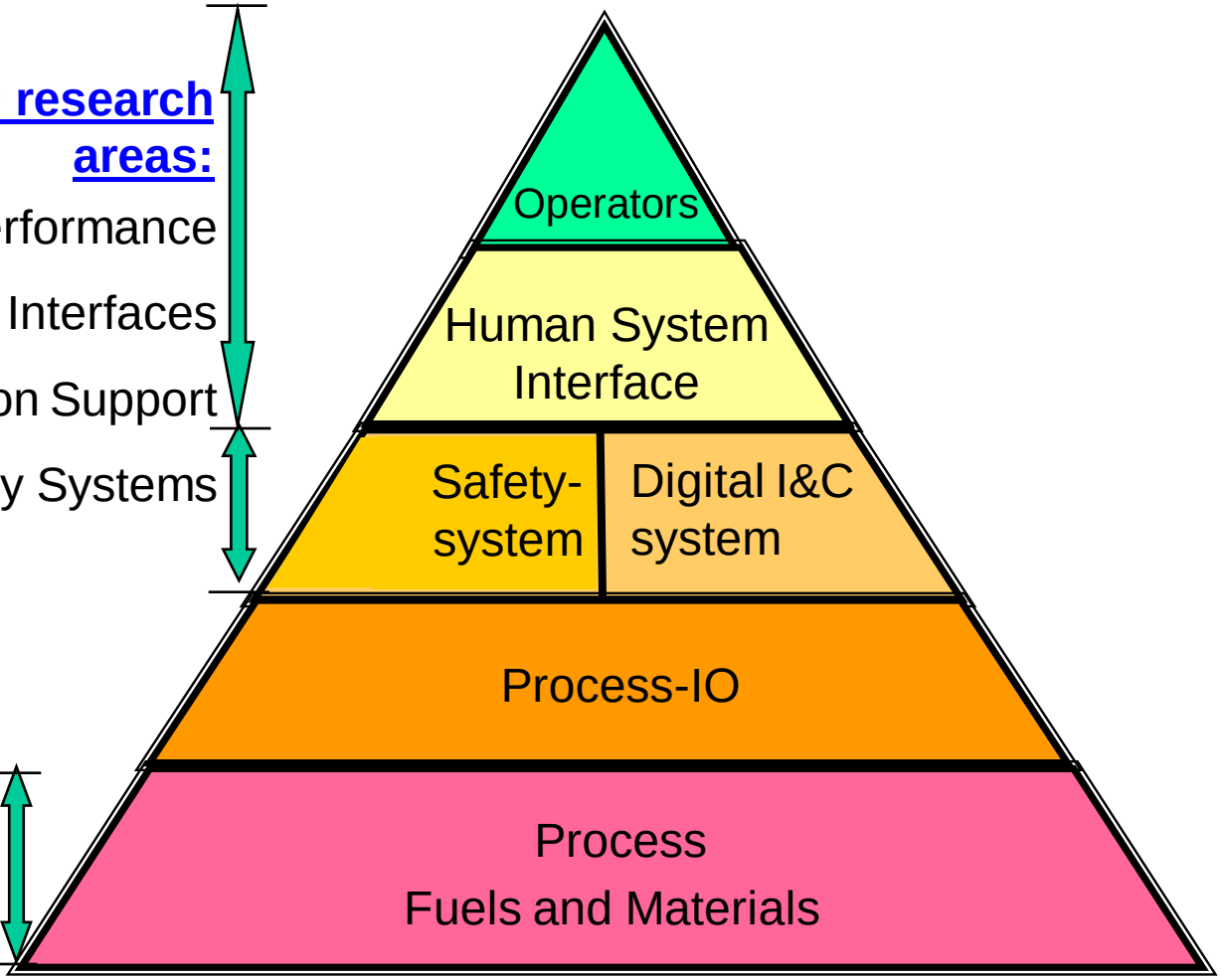
Safety Systems

Halden Fuel and Material research areas:

Fuel behavior in normal operations and transients

Clad corrosion and water chemistry issues

Plant lifetime assessments

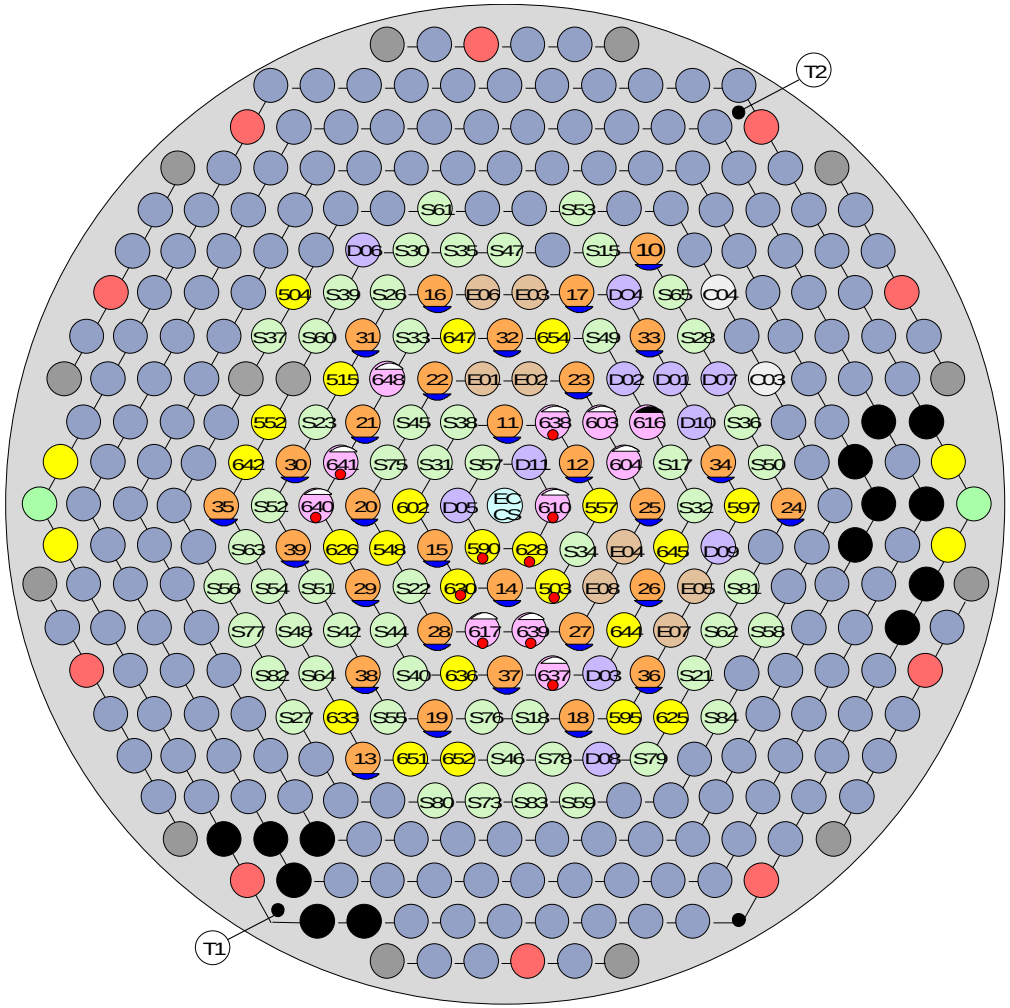


Overview of the research activities in the Fuels and Materials area at the Halden Reactor Project

HBWR – Reactor hall

Instrument workshop

The Halden Reactor - HBWR



- 20 MW heavy water reactor at 34 bar and 235°C
- Height of active core is 80 cm
- Hexagonal array of 300 channels within pressure tank
- Rings 1-6 used for experiments (about 30/110 positions used)
- Experimental channels directly in HBWR (71 mm in diameter)
- 8-10 loops system in operation at any given time (32 to 45 mm in diameter)

Objectives for Fuels & Materials Research at HRP

- Fuels
  - Support development of different fuel variants and new types of fuel
  - Provide data for fuel behaviour model development, verification and validation
  - Show compliance of fuel performance with design, operational and safety criteria
  - Assess safety criteria with respect to available margins and reasonableness
- Materials
  - Expand databases for plant lifetime extension assessments
  - Assess core component ageing mitigation measures

Achieving Fuels Research Objectives at HRP

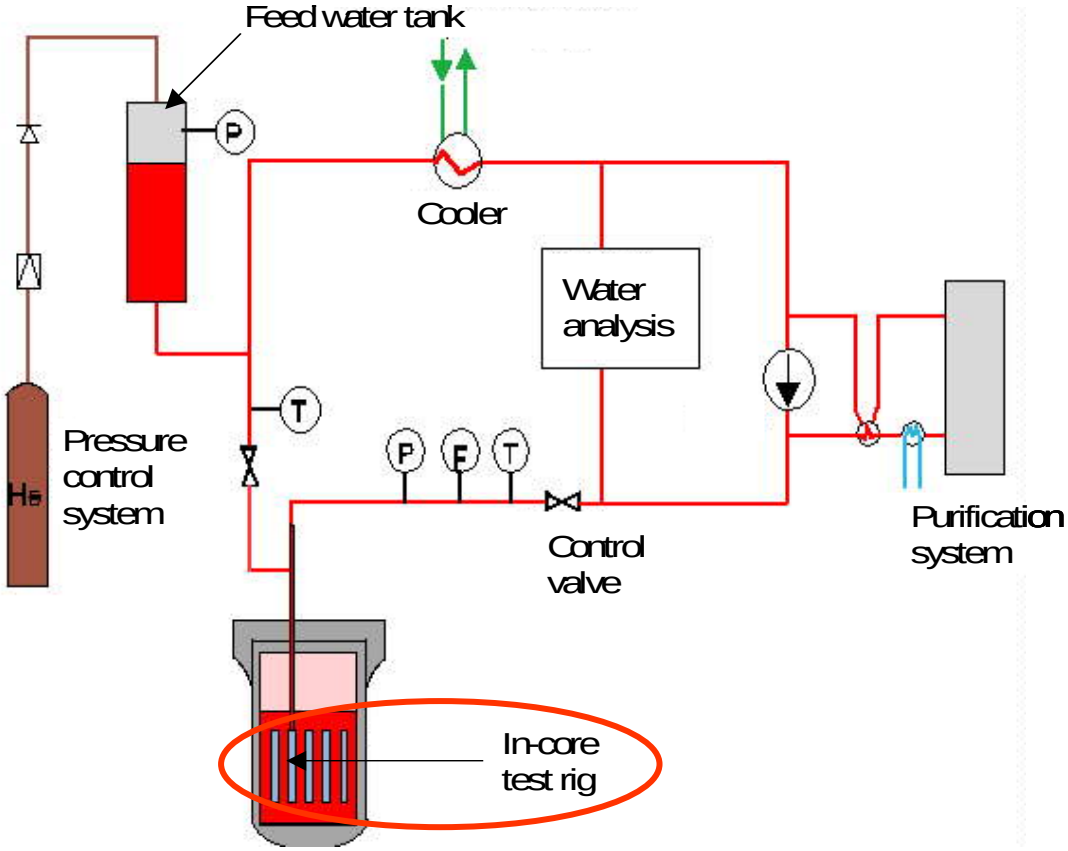
By comprehensive assessments of in-pile performance of fuels using HRP's facilities and capabilities:-

1. The HBWR test reactor
   - Dedicated to fuel & materials testing
2. Instrumented test rigs (IFAs)
   - Capable of implementing different *local* modes of operation (steady state, load follow, ramping, transients) and control (temperature, stress)
3. In-core instrumentation
   - Versatile range of instruments for making reliable measurements of a wide range of parameters
4. A hot-cell facility
   - Fabrication of instrumented test fuel rods and material test specimens
   - Re-fabrication and instrumentation of commercially irradiated fuels and materials
   - Fuel (pellet) production with wide range of enrichments
   - Post irradiation examination (PIE)

Special Capabilities of HBWR + Test Rigs

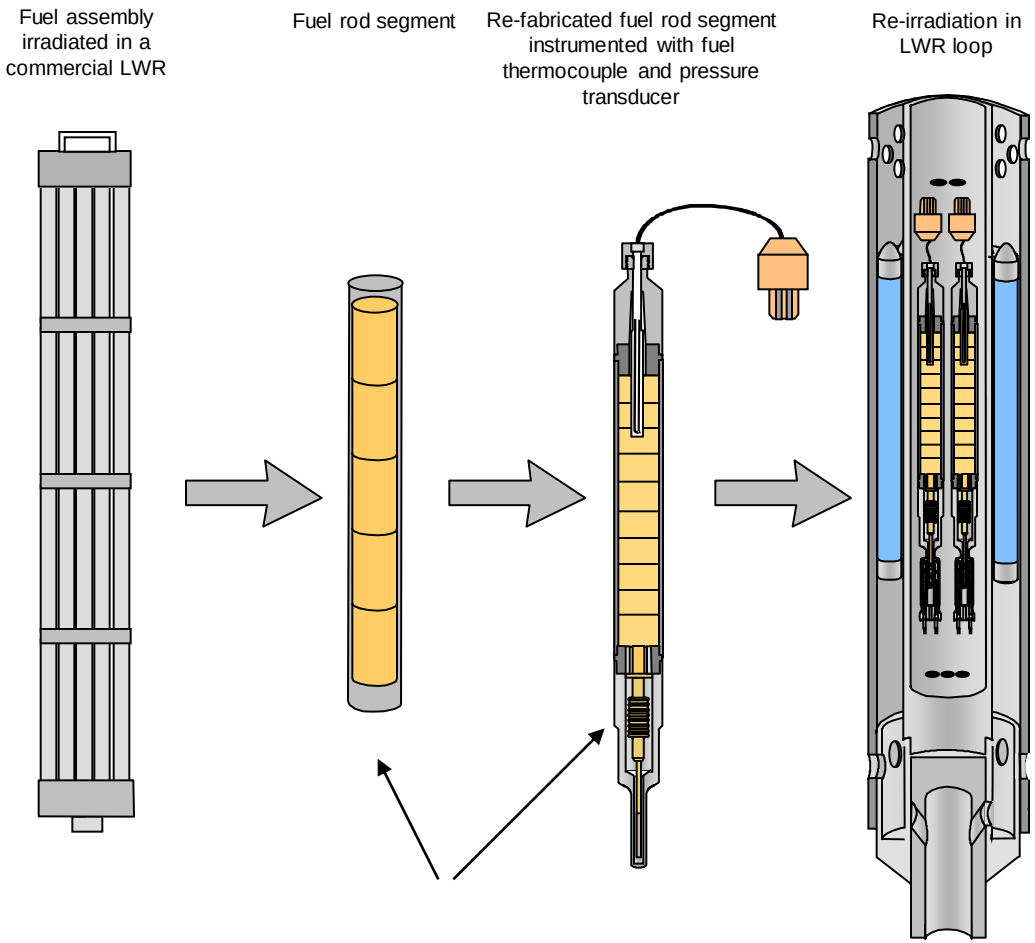
- Increasing emphasis on testing fuel under as close to "real situation" as possible plus an increasing need for well qualified data from **ever higher burn-up fuel**
- The HBWR Loop Systems
  - Specialised and dedicated loop systems built and operated within the HBWR to simulate thermal-hydraulic and water chemistry conditions representative of those (current or planned) for commercial NPPs
- Re-fabrication of commercial fuel
  - To avoid long base irradiation in HBWR – an important advance has been ability to re-fabricate and instrument sections of commercially irradiated fuel rod
  - Also allows in-core performance of fuel in excess of current burn-up limits for power reactors to be studied

The HBWR loop system



- Test rigs placed in pressure flasks connected to external loop systems
- Allows testing of fuel under simulated BWR, PWR or PHWR conditions:
  - Coolant pressure
  - Coolant temperature
  - Water chemistry
- Used for cladding corrosion testing and e.g. PCMI fuel testing

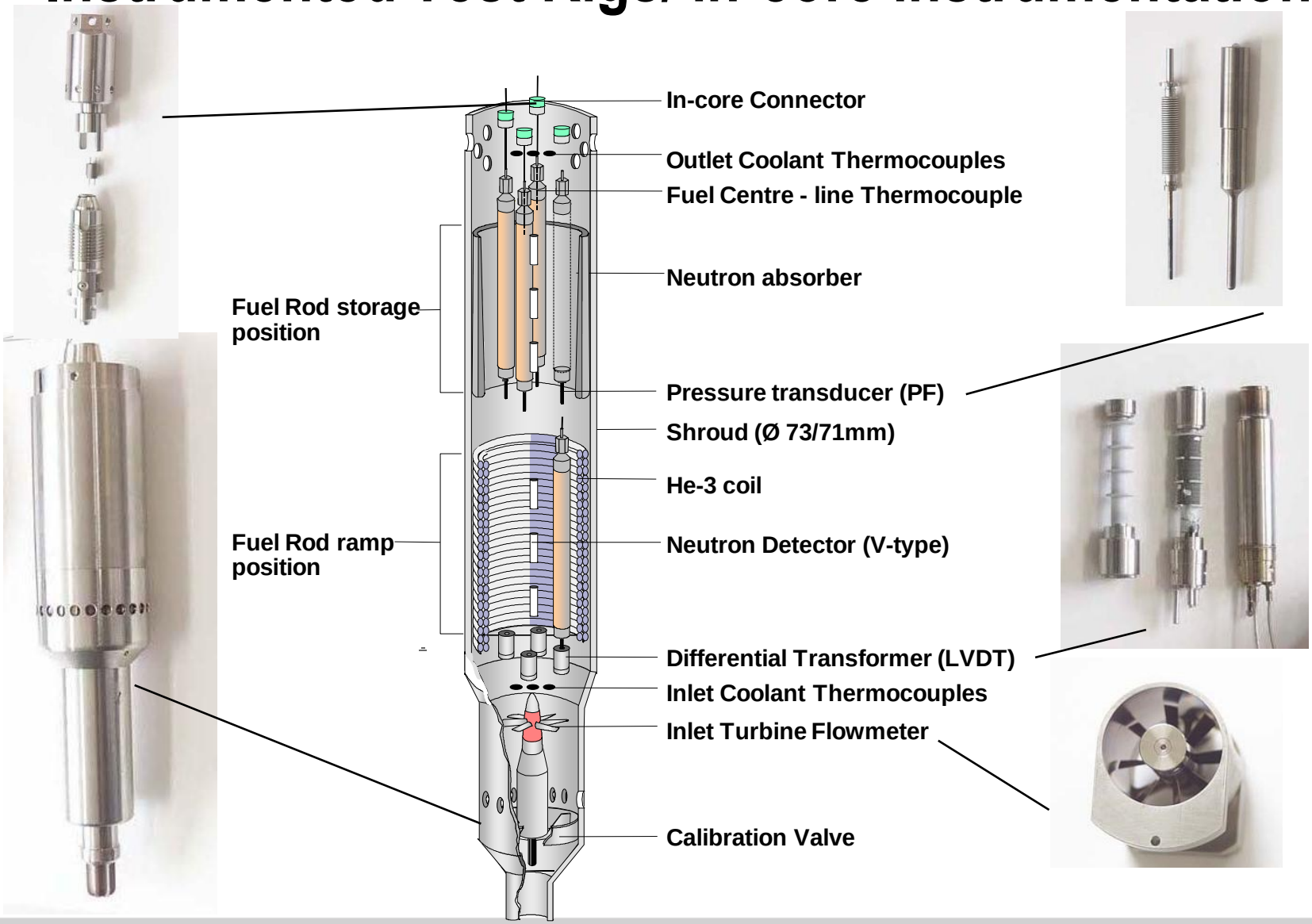
Re-fabrication of commercial fuel



- Fuel segments taken from commercial NPPs
- Medium and high burn-up
- Re-fabricated and instrumented in hot-lab
- Same instrumentation possibilities as for fresh fuel
- Use of in-core connectors (with mechanical sealing) for thermocouples and gas lines

NPP -> IFE Kjeller hot-cell -> HBWR

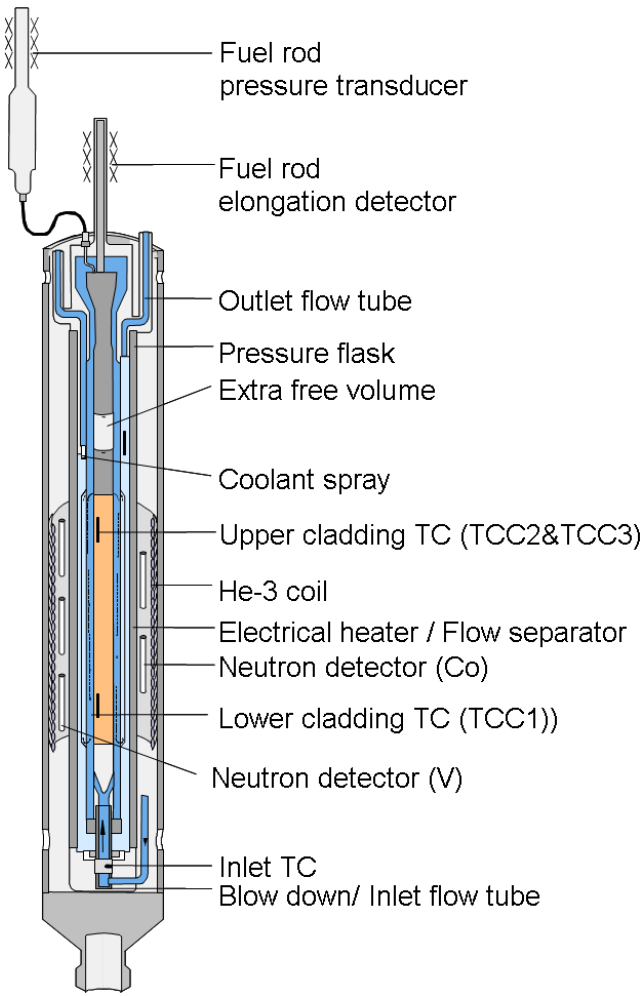
Instrumented Test Rigs/ in-core instrumentation

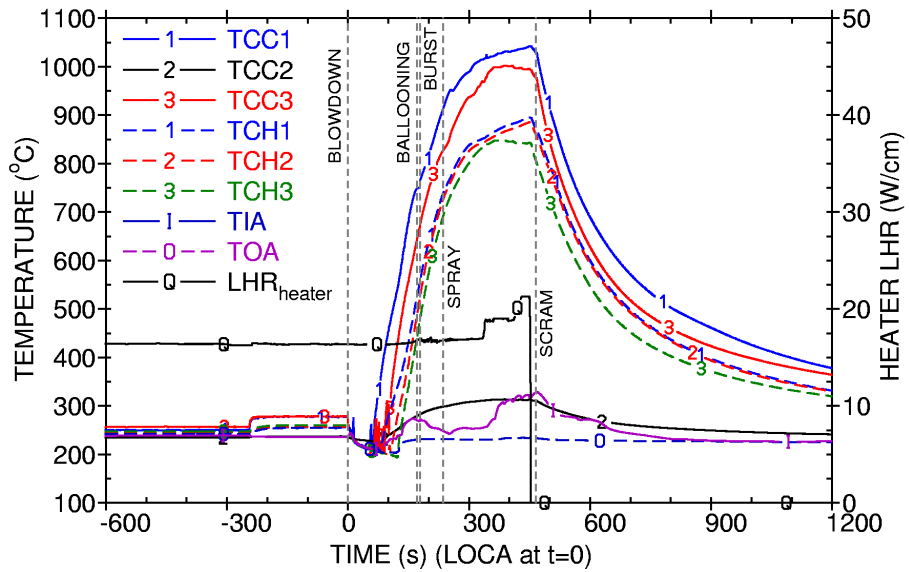


In-pile measurements made on fuel rods in the HBWR - fuel performance issues to which they relate

• Fuel Temperature	Heat transfer (fuel thermal conductivity, gap conductance)
• Rod Internal Pressure Change	Fission gas release, fuel densification & swelling
• Fuel Stack Length Change	Fuel densification & swelling
• Fuel Cladding Length Change	PCMI, (or when no PCMI, surface heat transfer, growth)
• Fuel Rod Outer Diameter Change	PCMI, (or when no PCMI, creep & growth, corrosion)

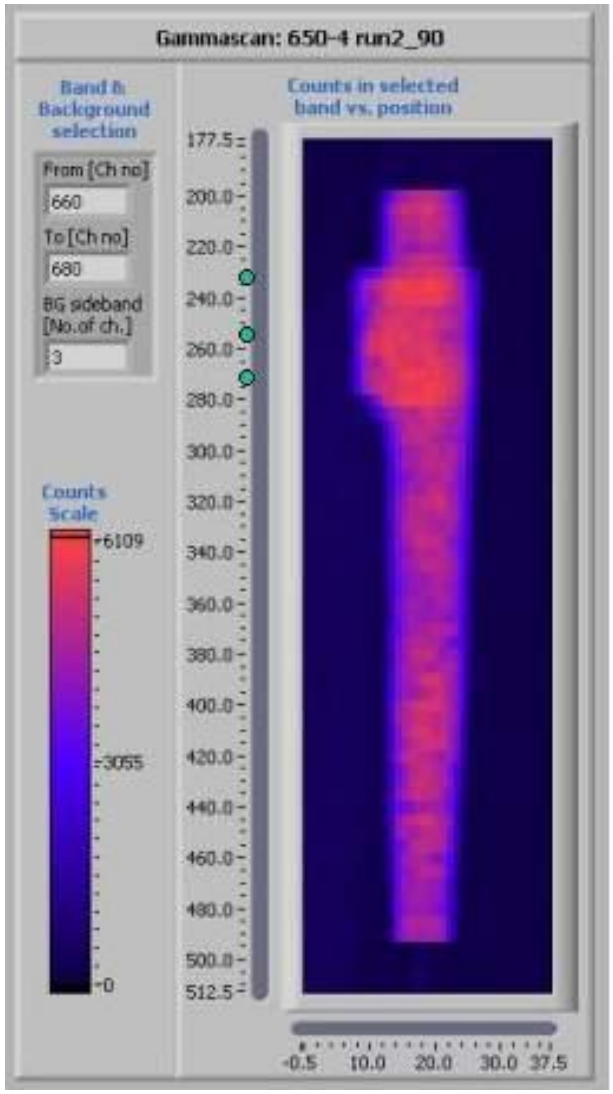
Example 1: Fuel response to transient testing: LOCA



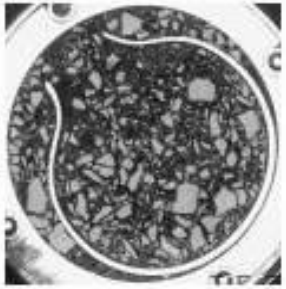


- To complement out-of-reactor testing and to investigate in-reactor effects that cannot be obtained in out-of-reactor tests:
  - Effect of fuel-clad bonding and fuel fragment relocation on clad ballooning
  - Effect of overheating of central fragments

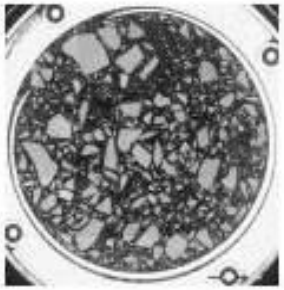
Some recent observations



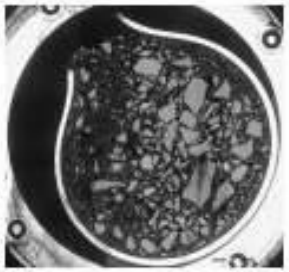
Balloon zone (200-280mm)



235mm



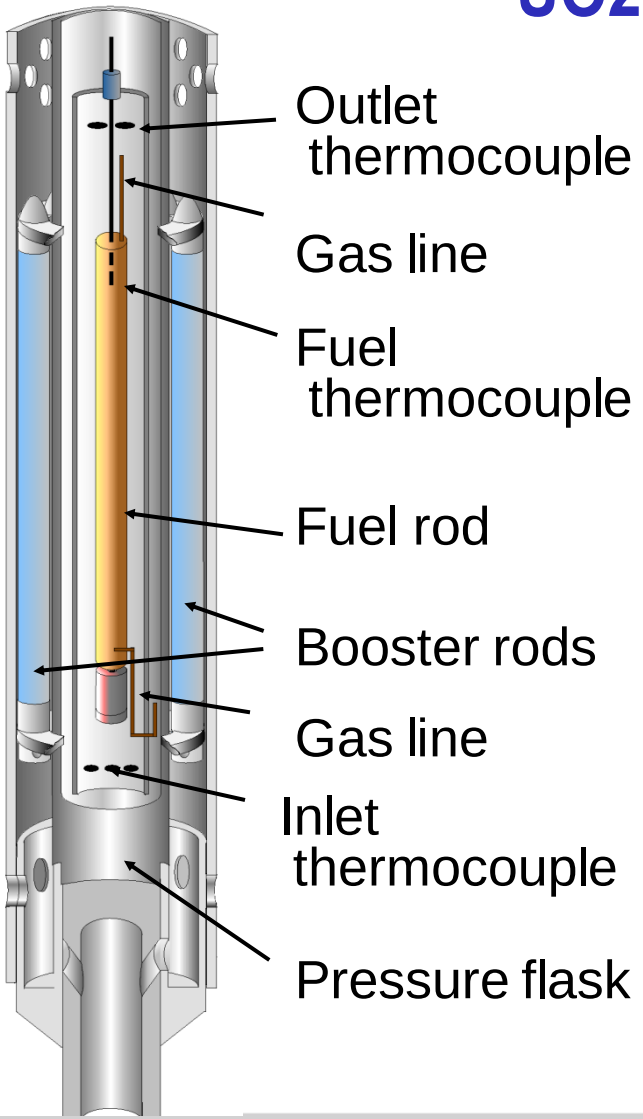
255mm



275mm

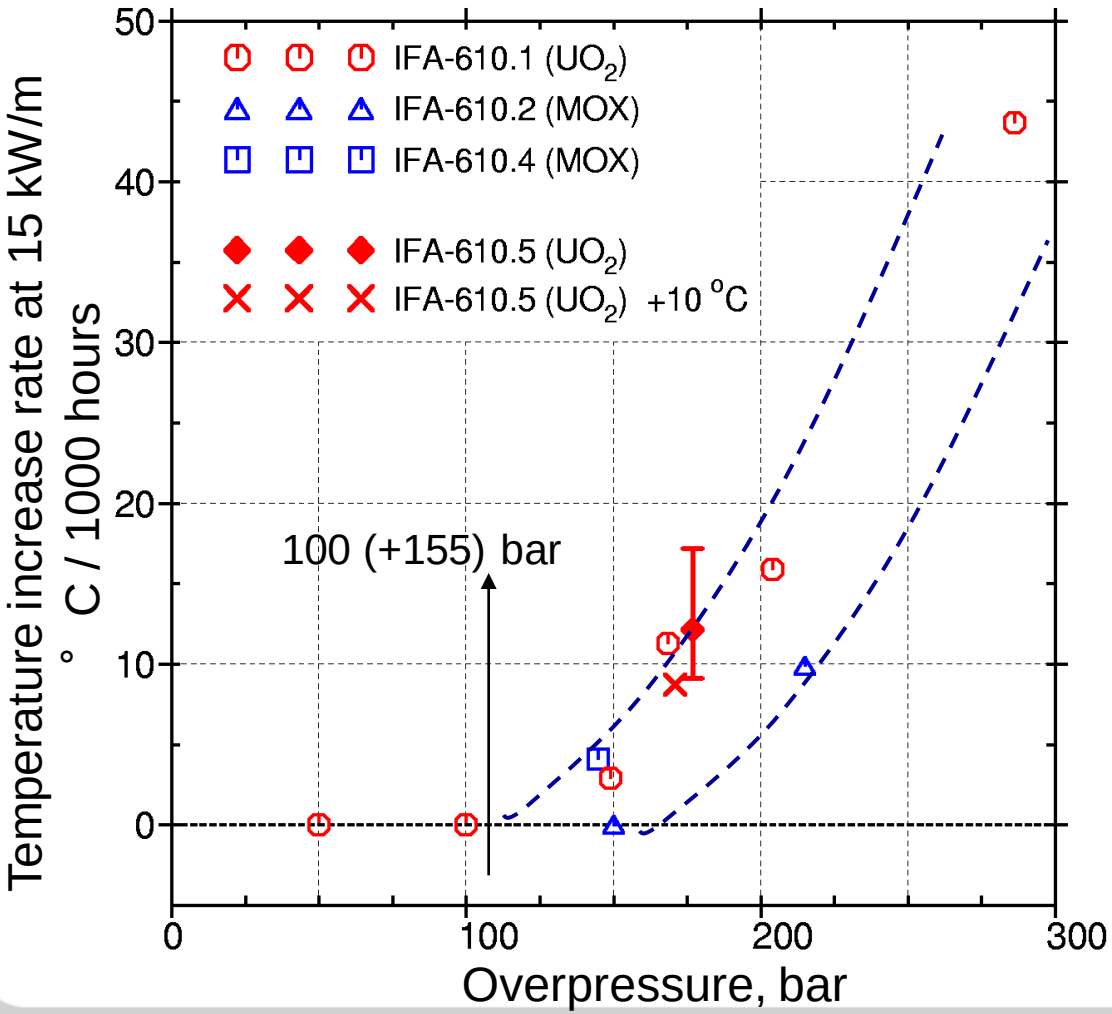
Considerable fuel fragmentation and relocation in IFA-650.4

Example 2: Tolerable rod overpressure in UO2 and MOX fuel rods



- PWR operation conditions
- Pressure flask surrounded by 12 booster rods
- Gas flow lines
  - Overpressure
  - Hydraulic diameter measurement and gamma-spectroscopy
- Thermocouple (TF) with in-core connector
- Cladding extensometry (EC)

Tolerable Rod Overpressure Tests



Observations

- Rate of temperature increase correlated with overpressure
- Thermal feedback occurs only at considerable overpressure (>100 bar)
- Below this threshold, clad creep-out is sufficiently compensated by fuel swelling, and no net thermal feedback becomes apparent

Material Programme/ Plant Lifetime Extension

- Focus of Halden materials studies
  - Crack growth rate and crack initiation studies
    - test materials with wide range of dose levels
    - extend and systematise the database and modelling
  - Develop further understanding of mitigation measures (water chemistry, post irradiation heat treatments)
    - when do mitigation measures become less effective?
  - Irradiation creep and stress relaxation studies
    - pre-loaded components subject to creep / stress relaxation; design requires that a minimum load be maintained throughout service
    - data needed for component analysis & design to minimise or prevent cracking / failure of loose bolts

Example 3: Crack growth & crack initiation studies

- Develop understanding of key parameters:
  - material, dose , temperature, water chemistry, electrochemical corrosion potential, stress/stress intensity controlling IASCC initiation & growth
- Assess benefits of countermeasures
  - e.g. Hydrogen addition in BWRs; post irradiation annealing treatments

- Investigations performed in representative thermal hydraulic, coolant chemistry and radiation conditions
- On-line instrumentation

Example 3: Crack Growth Rate Investigations

Objectives

- Measure on-line cracking response of materials (SS 347, 304, 316) retrieved from commercial reactor components (top guide, control blades, baffle bolts)

- Compare & quantify CGRs in BWR (280-290 °C, O_2 and H_2)

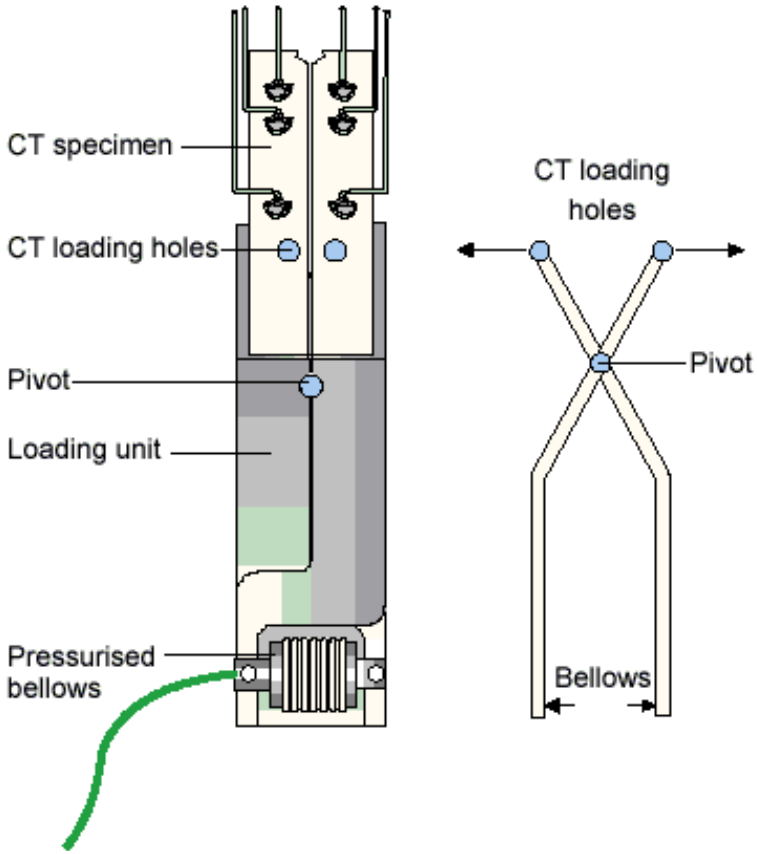
  vs. PWR (320-340 °C, Li, B, H_2) conditions

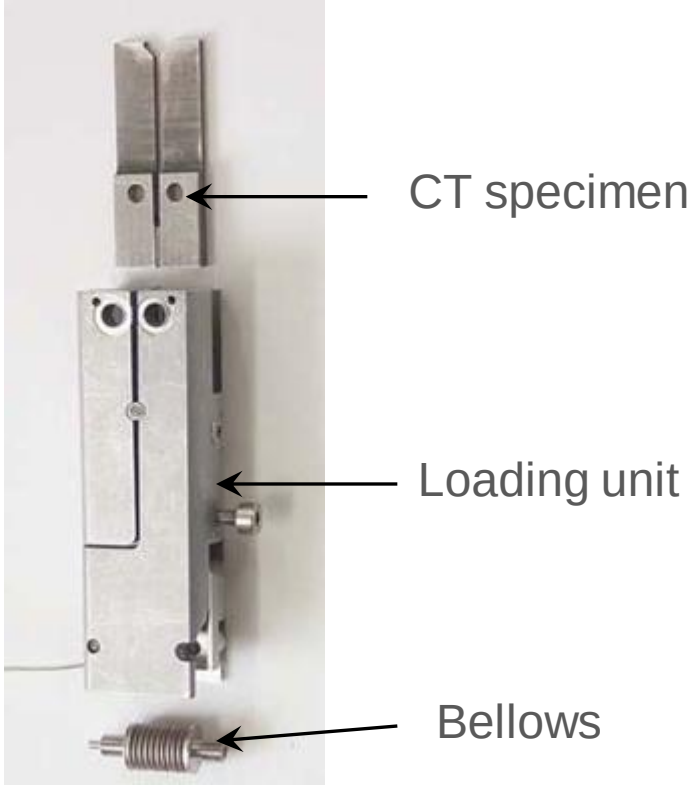
- Study cracking response as affected by

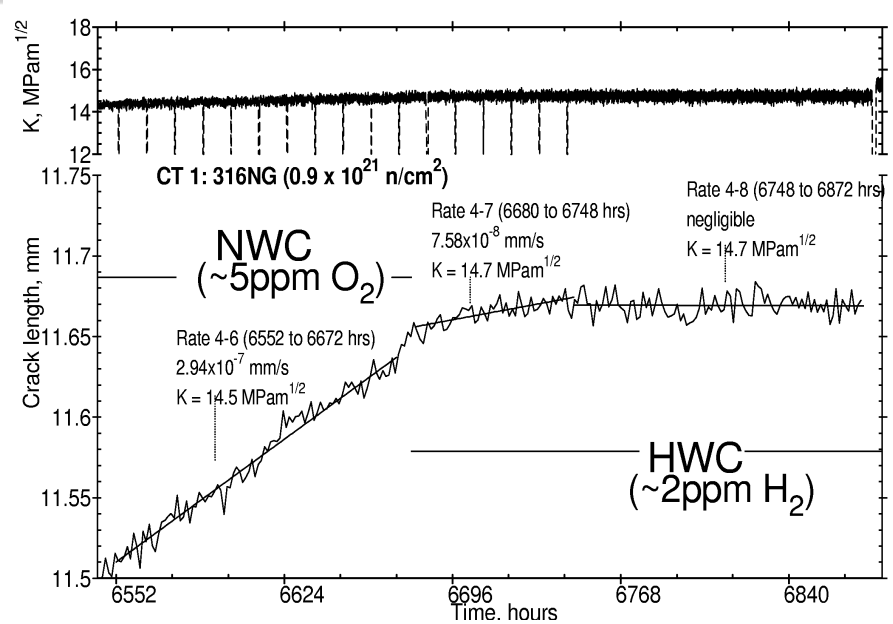
  - stress intensity (K) level

  - fluence (7×10^{19} n/cm^2 to 2.5×10^{22} n/cm^2)

Instrumented CT with pressurised bellows

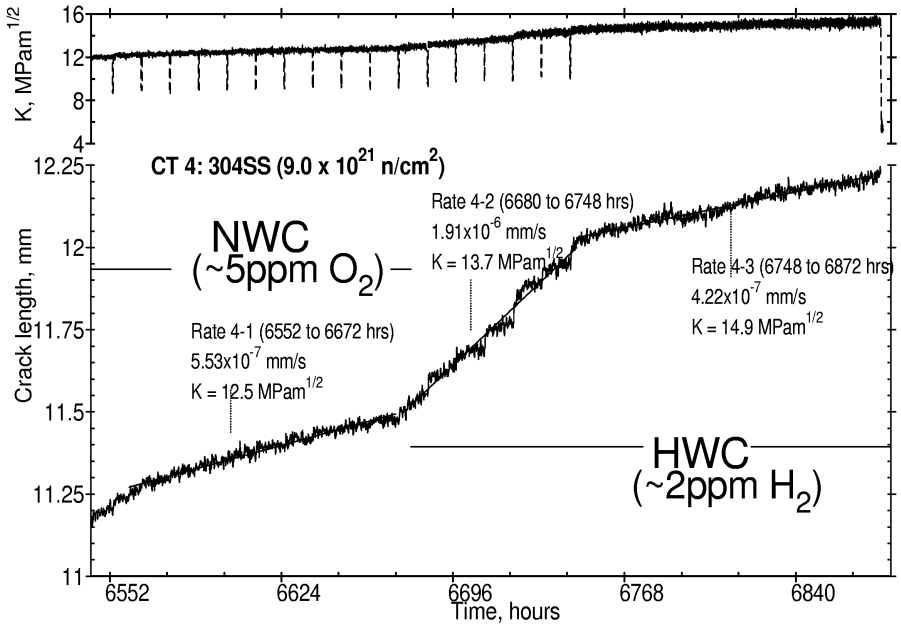






Response of low fluence CT to the addition of H_2.

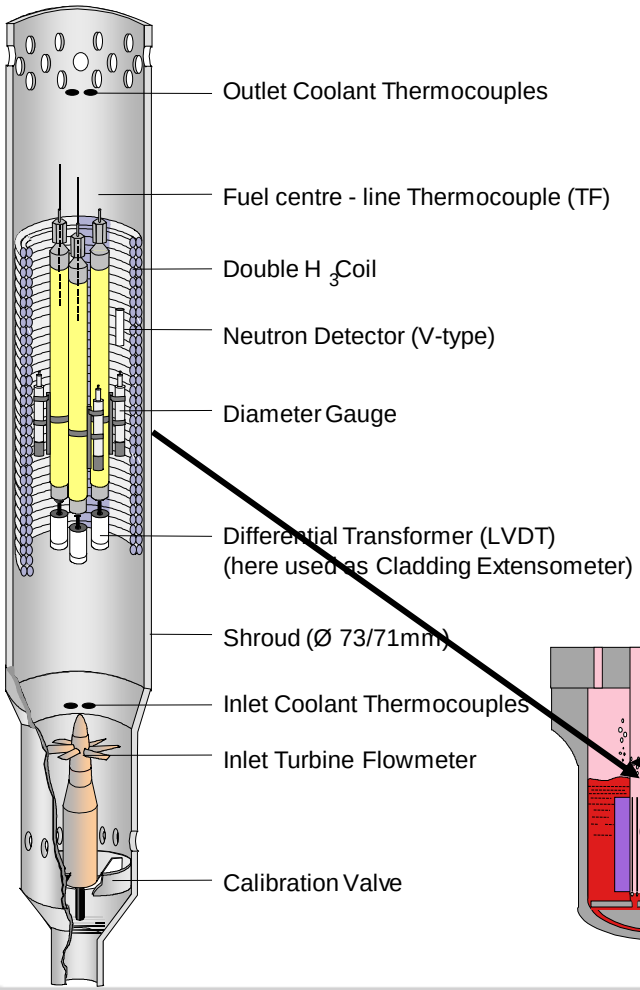
A clear reduction in growth rate is evident.



Response of high fluence CT to the addition of H_2.

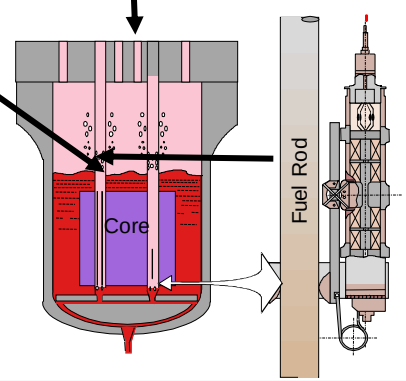
No change in growth rate is recorded.

Summary – Fuels & materials experiments



Fuel & Materials in pile Joint program tests 2006-2008	2006	2007	2008	Unique tests
In-pile tests	13	13	13	17
additional PIE	2	2	2	6
Rigs in pile/year	15	15	15	23

Fuel & Materials in pile Bilateral tests 2006-2008	2006	2007	2008	Unique tests
Japan	4	8	9	15
Korea	2	2	2	2
Sweden	1	2	2	2
France	1	3	1	3
USA	1	1	1	1
Canada	1	1	1	1
Rigs in pile/year	10	17	16	24
Rigs in pile/year	25	32	31	47

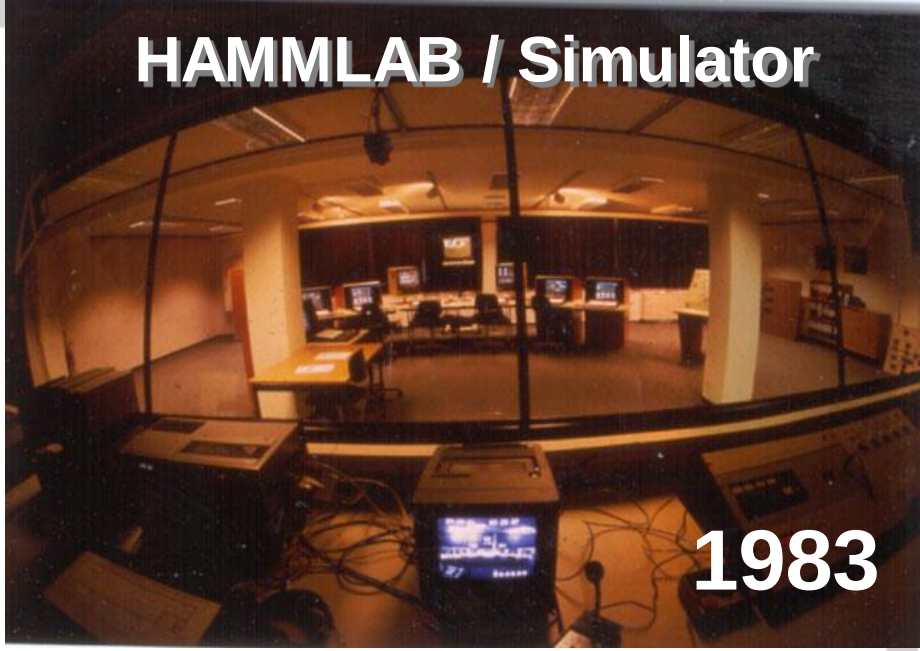


Summary Fuels and Materials program

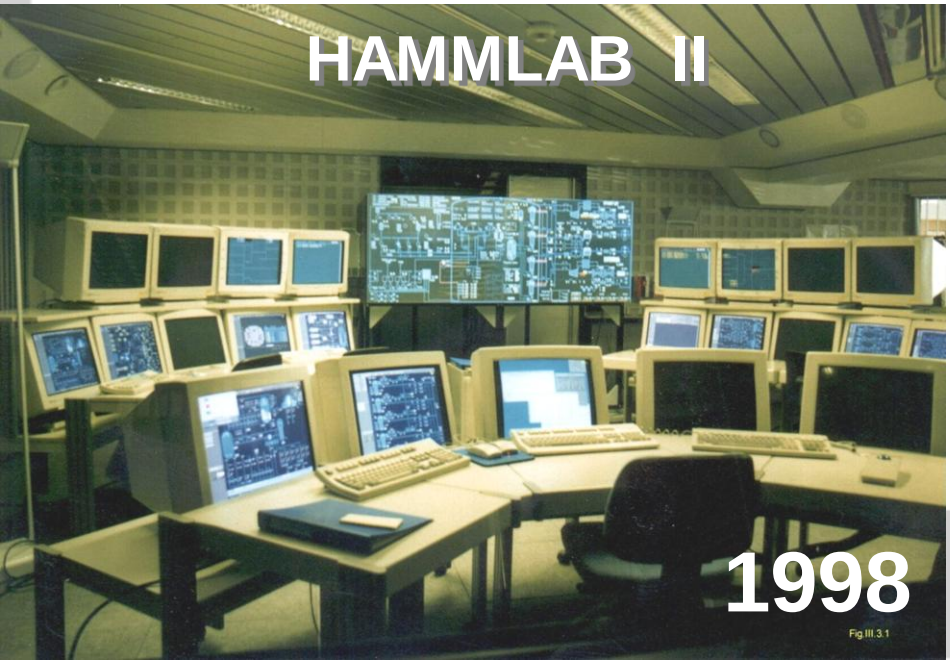
HRP's fuel and materials testing program is aimed at improving understanding and validating fuel performance codes ....ultimately with the goal of increasing reactor safety and improving economy

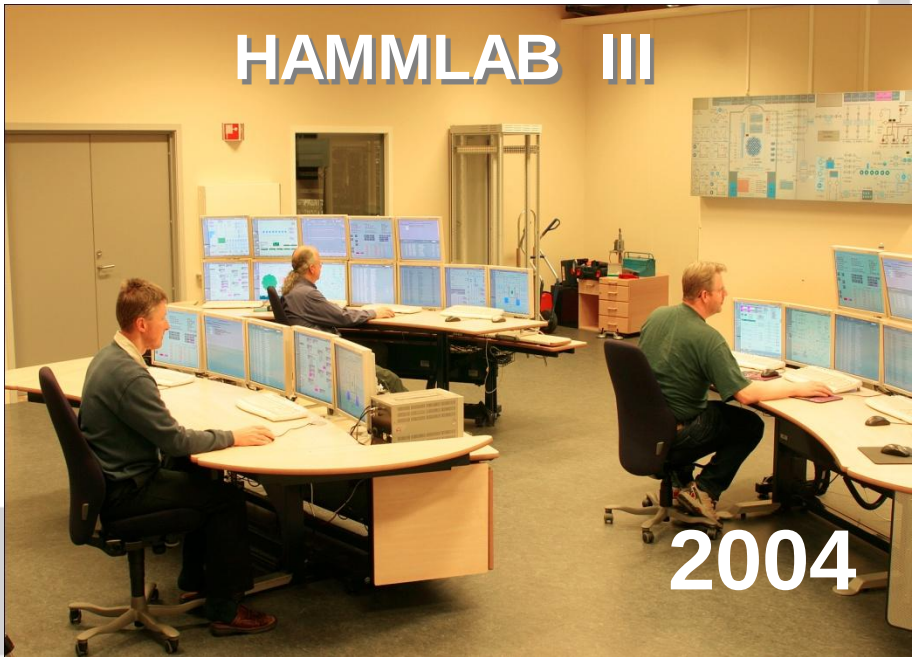
- Use of reliable and accurate in-core instrumentation to measure all relevant parameters under controlled operating conditions
- Possibility for “separate effects” investigations
- Fuel rods with different sensors enable better understanding and provide consistent data for modelling purposes
- Re-fabricating commercially irradiated fuel rods extends the relevance of fuel rods that can be studied (high burn-up)
- Loop systems allow tests to be conducted under representative thermal-hydraulic conditions, which is important for some forms of investigation e.g. PCMI studies
- It is expected that in the future more emphasis will be placed on having testing facilities and instruments available for water chemistry studies e.g. on-line sensing of cladding corrosion

Overview of the research activities in the MTO (Man-Technology-Organisation) area at the Halden Reactor Project



MMS – MTO research facilities





MTO-lab 2010

Hammlab and Experimental control room

Halden VR-Center (HVRC)

Experimental control room, Integration room and Collaboration Room

HAMMLAB IV, spring 2009

Model illustrating the control levelsof a modern NPP

Halden MTO focus areas:

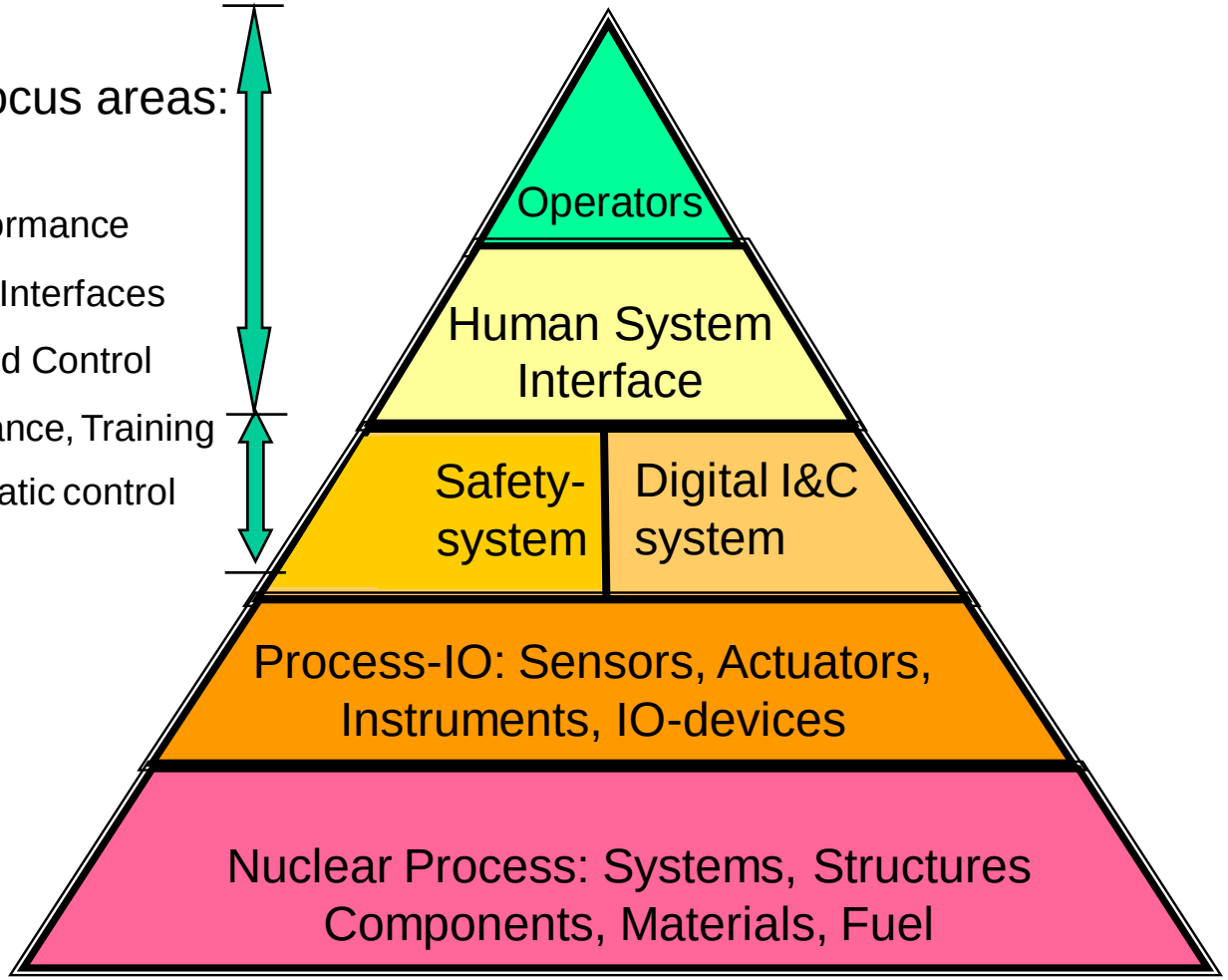
Human Performance

Human System Interfaces

Surveillance and Control

Planning, Maintenance, Training

Safety and Automatic control



MTO R&D Areas

Simulator technology

Safety critical SW

Simulator experiments methods and measures

Human reliability, PSFs, Task complexity

Operational culture

Operation Support Systems

Human factors

Work Processes

Signal Validation

Control room design

Function Allocation

Advanced Alarm Systems

Teamwork

Integrated System Validation

Diagnosis Systems

Work practise in Digital CR

Coping with Automation

Computerised Procedures

Team Transparency

Staffing strategies

Human System Interfaces

Outage Control Centres

Control room design and verification tool

Large Display Panels

Outage LDP and HSIs

Wearable control room

Innovative HSIs

Teamwork in Outage

Automation HSIs

Performance Monitoring

Ubiquitous computing

HSI tools

Condition Monitoring

Handheld devices

3D Radiation visualisation

Automatic control

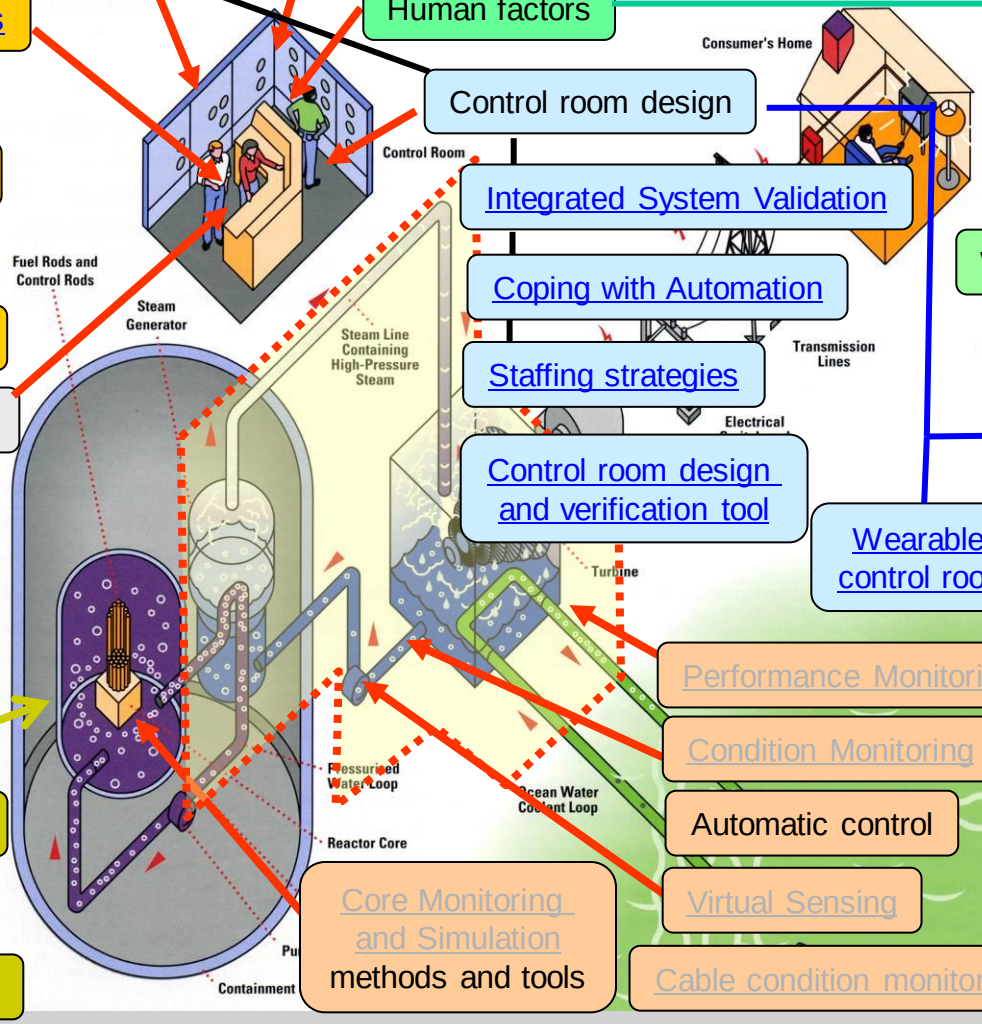
Maintenance planning

Virtual Sensing

Core Monitoring and Simulation methods and tools

Decommissioning planning

Cable condition monitoring



Summary

- Halden Reactor Project a center for nuclear safety research since 1958
  - 18 countries participate in a jointly funded research program
  - Halden Reactor is the most versatile nuclear test reactor in the world
  - Hammlab is a unique test bed in the MTO area
- More countries and companies are interested in participating in the HRP
- The Halden Board of Management recently unanimously expressed their willingness to support the continued operation of the Project

Fredriksten fortress @ Halden: **The Nuclear Fortess**

Board
Terje Overvik GdF
(chairman)

COE
Kjell H. Bendiksen

Vice COE
Eva S. Dugstad

HALDENPROJECT
Fridtjov Øwre

IFE facts:

- 5 research sectors
- 2 research reactors
- ca. 630 employees
- Turnover ca. 75 mill Euro

Nuclear technology and Physics
Eva S. Dugstad

Nuclear Safety and Reliability
Margaret McGrath

Safety Man-Technology-Organization
Fridtjov Øvre

Energy- and Environment
Bjørg Andresen

Petroleum-technology
Dag Thomassen