FUEL ROD PERFORMANCE MEASUREMENTS AND RE-INSTRUMENTATION CAPABILITIES AT THE HALDEN PROJECT

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Abstract

In the area of instrumentation technology, the Halden Project has developed several different types of sensors enabling on-line measurement of fuel rod behaviour such as mechanical deformation of fuel stack and cladding, and fuel rod temperature and pressure. In-core measurements using a linear voltage differential transformer as a base instrument enables on-line monitoring of parameters such as fuel stack elongation, cladding elongation, fuel centre temperature and fuel rod pressure. Other on-line information, for example build-up of cladding oxide layer and detection of the point of dry-out can be derived from the measurements outlined above. Multiple instrumentation, i.e. having instruments in both ends of one or several fuel rods is possible, giving extensive on-line information on fuel rod behaviour during power operation in the reactor. Another sophisticated instrument, especially developed for in-core monitoring, is the diameter gauge which enables on-line measurement of cladding diameter changes due to pellet cladding interaction and creep.

For high burn-up applications it is desirable to utilise standard light water reactor fuel rods or segments pre-irradiated in a commercial reactor. A method for re-instrumenting an irradiated fuel rod with a pressure transducer, cladding extensometer and fuel centre-line thermocouple has been perfected at Halden. This technique enables investigations on fuel thermal performance at high burn-up to be carried out without the need of long term irradiation in a test reactor and without the drawback of thermocouple de-calibration corrections. The main motivation for these types of measurement is that during irradiation the fuel may undergo substantial changes in physical properties, e.g. reduction of conductivity and build-up of a pellet outer rim which may impair the fuel thermal performance.

In addition, the materials testing programme at Halden includes in-pile investigations aimed at addressing Irradiation Assisted Stress Corrosion Cracking, the materials degradation phenomenon that affects the structural integrity of core component materials such as stainless steels and nickel-base alloys. The main objective of the IASCC studies has been to evaluate the effects of the fundamental parameters stress, environment and microstructure on the crack growth behaviour of reactor internals materials in conditions representative of commercial Boiling Water Reactors (BWRs).

Introduction

The Halden Project has more than thirty years experience in performing complicated in-core measurements and experiments during power operation in the Halden Boiling Water Reactor (HBWR), and a wide range of sensors, equipment and techniques have been developed for this purpose.

Proper application of instruments is as important as having available high quality instruments, and in this respect the staff has gained considerable experience through installing and using more than 2500 in-core instruments. The measurements are performed in the Halden reactor during operation at power, i.e. in a water environment at 240°C and 34 bar, and in the presence of neutron and gamma radiation. The measuring techniques are also employed in special in-core loops operating under prototypical Light Water Reactor (LWR) pressures (up to 155 bar) and temperatures (up to 325°C).

For high burn-up applications, techniques have been developed for re-instrumenting standard fuel rods or segments, pre-irradiated in a commercial reactor. Re-instrumentation techniques are applied for inserting centre-line fuel thermocouples and fitting pressure transducers or cladding extensometers to irradiated rods.

Fuel rod performance

In the area of fuel rod instrumentation technology, the Project has developed several different types of sensors enabling on-line measurement of fuel rod behaviour such as mechanical deformation of fuel stack and cladding, and variations in fuel rod temperature and pressure.

In order to study fuel performance, the following main parameters need to be assessed during long-term irradiation tests [1]:

- Fuel centre temperature, in particular thermal property changes as function of burn-up.
- Fission gas release as function of operating power and burn-up. The fission gas retention properties of the fuel, i.e. the release “threshold”, are to be assessed.
- Fuel swelling as affected by solid fission product production and gaseous fission product deposition at the grain boundary.
- Pellet-cladding interaction, defined here in terms of cladding axial deformation induced by pellet-to-cladding contact.

The following instruments are utilised to characterise the above fuel parameters:

- Fuel thermocouple or expansion thermometer which provide measurements of the fuel centre temperature. The expansion thermometer is recommended for long-term fuel studies.
- Bellows pressure transducer, which provides data on the fission gas release by means of measurements of the rod inner pressure.

- Fuel stack elongation detector, which provides swelling data in terms of axial expansion of the fuel stack referred to standard conditions.

- Fuel cladding elongation detector, which provides data on the onset of pellet-cladding interaction as a function of operating power and burn-up.

- Diameter gauge, which provides data on cladding diameter variations due to pellet-cladding interaction and materials creep.

These instruments, with the exception of the fuel thermocouple, operate by means of a displacement of a magnetic core inserted in a linear voltage differential transformer. Thus, for their operation, no cable penetration into the fuel rod is required. Other on-line information, for example build-up of cladding oxide layer and detection of the point of dry-out can be derived from the measurements listed above. Multiple instrumentation, i.e. having instruments in both ends of one or several fuel rods is possible, giving extensive on-line information on fuel rod behaviour during power operation in the reactor. A more detailed description of the instruments is given below.

Linear Voltage Differential Transformer (LVDT)

A component of importance for many measurements is the Linear Voltage Differential Transformer (LVDT). The design consists of a centre coil used as a primary coil with two outer, secondary coils connected in opposition. The coils are wound from ceramic insulated wire on non-magnetic, austenitic stainless steel housing which is insulated from the ground by means of sprayed aluminium oxide.

Located concentrically inside the coil system is a movable magnetic core made from low carbon chrome steel. The position of the core amplifies and influences the symmetry of the magnetic field in the coil system when a constant alternating current (AC) is applied to the primary coil. The result is a linear relationship between the position of the core and the voltage difference produced in the secondary coils. The primary coil of the LVDT is excited with a 50 mA, 400 Hz current. The linear range and sensitivity is ± 2.5 mm (Type 5) ≈60 mV/mm [2] with a calibrated accuracy of 0.6 %. Individual instrument calibration is carried out at room temperature, and at specified temperatures up to 350°C. The LVDT (in conjunction with the bellows pressure transducer) is illustrated in Figure 1.

Fuel Centre-line Thermocouple (TF) and Expansion Thermometer (ET)

Fuel Centre-line Thermocouple (TF)

Fuel pellet centre temperatures are measured with a high-temperature thermocouple inserted in the fuel column (hollow pellets). Temperatures up to 1800°C are measured by means of a tungsten 5% rhenium / tungsten 26% rhenium thermocouple in a molybdenum / 50% rhenium sheet (outer diameter 1.5 - 1.6 mm), insulated by high purity beryllium oxide (99.9%) and connected to a compensation cable. De-calibration of the tungsten alloy thermocouples due to irradiation including transitions in the material has been studied at the Project, and correction procedures have been developed.

Expansion Thermometer (ET)

Fuel centre temperature measurements through thermal expansion of a central metal rod sensed by a LVDT has been applied. The principle is to measure the thermal expansion of a tiny rod, made from refractory metal (tungsten 0.8% / zircaloy-oxide) and capable of withstanding very high temperatures (up to 2500°C), which penetrates the whole fuel column (hollow pellets). In this case, the magnetic core is fixed onto one end of the expanding metal rod, which typically has a diameter of 1.5 mm.

The method enables measurement of the average fuel rod centre temperature without any cable penetration into the fuel rod, i.e. the temperature is sensed from the fuel rod exterior. The measurement is unaffected by local conditions along the fuel stack. Further advantages include robust construction (as compared with the rather delicate wires of the thermocouples) and easy interchange of fuel rods. The method also facilitates high temperature measurements where thermocouples tend to have limited lifetime.

Bellows Pressure Transducer (PF)

A miniaturised bellows made from stainless steel or Inconel is mounted inside a fuel rod end plug (with access to the plenum) for the purpose of measuring the rod pressure. The principle is that the bellows (which is sealed) contracts under the effect of the increasing rod pressure, causing the movement of a magnetic core mounted onto the bellows. The movement of the magnetic core is sensed by a LVDT.

Measuring ranges up to 150 bar are available. To reduce materials creep at high temperature and radiation intensity, the bellows are pre-pressurised (inside) and conditioned for several days at high pressure and temperature. The pressure transducer can be systematically re-calibrated during reactor outages using well established procedures developed at the Project.

The bellows differential pressure will in addition to release of fission gases, be dependent upon fuel densification / swelling characteristics, changes in gas temperatures and fuel / cladding thermal expansion during operation. Densification will lower the fuel rod internal pressure, while swelling and gas temperature effects and fuel differential expansion will contribute to an increase.

Fuel Stack Elongation Detector (EF)

In order to measure movements of the fuel column, a magnetic core is spring loaded against the fuel column end pellet. Using a LVDT, the displacement of the core provides data on a) fuel thermal expansion, as measured during power increases or decreases, and b) fuel densification / swelling, as measured during constant power operation or various shutdowns during the course of the irradiation.

For the densification / swelling measurements, one has to consider that only *axial* dimensional changes are measured with this method. Comparison with post irradiation fuel density data, however, has demonstrated that the fuel volume changes are isotropic, such that the volume change (in per cent) is three times the change in axial length.

Fuel Cladding Elongation Detector (EC)

When a LVDT is used as a cladding extensometer (EC) in a fuel assembly or irradiation test rig, the core is fixed to the free-moving end of the fuel rod, while the coil system is supported by zircaloy stringers fixed in parallel to the fuel rod.

During power ramps, the cladding length increases due to thermal expansion. Beyond the power level at which pellet-cladding interaction (PCI) occurs, the cladding length exhibits a sharp increase because of axial straining of the cladding induced by fuel-to-cladding friction. This is a very good indicator of the onset of PCI. Changes of elongation data taken at zero power during reactor shutdown give a measurement of the permanent (non-elastic) deformation of the cladding material due primarily to irradiation creep.

In dry-out experiments, cladding length measurements can also be utilised to detect the point of dry-out, since a sudden increase of the cladding temperature produces a sharp increase of the cladding length. An experiment utilising this effect is currently being undertaken at the Project.

A new technique based on cladding length measurements has been proposed for determination of the thermal conductivity of zirconium oxide. The principle is that when the cladding elongates at increasing power due to thermal expansion, the oxidised cladding will be hotter and therefore elongate more. The difference in elongation will reflect the difference in cladding temperature and thus provides a measure of the oxide conductivity. The method has been successfully demonstrated in a feasibility test.

Another new technique using the cladding extensometer has recently been proposed for measuring the amount of stored heat in a fuel rod during reactor shutdown.

Fuel Rod Diameter Gauge (DG)

High sensitivity is required for measuring small diameter variations of the cladding during irradiation, and a special type of the differential transformer has been developed for this purpose, the so-called diameter gauge. In this type of transformer, the magnetic flux path is almost entirely enclosed in ferromagnetic material except for a few very narrow gaps. The coils are wound on a ferromagnetic core and the ferromagnetic armature is suspended in cross springs parallel to the coil system in such a way that when the armature moves, one magnet gap will increase while the opposite one decreases. The magnetic flux in the two halves of the coil system will vary in opposite directions thus producing a net differential signal.

The diameter gauge travels along the fuel rod producing an axial profilometry of the rod. Fuel rods used in connection with diameter gauge measurements are always equipped with end plugs equipped with three calibrated diameters (such that the gauge is calibrated for each run) as well as a position indicator, the latter giving the correct axial position of the measuring gauge. Diameter gauges may also be utilised for measurement of cladding elongation using V-notches on the end plugs as reference marks. A calibration run prior to irradiation is necessary to determine the exact distance between the notches.

The notches will cause sharp peaks on the diameter profile, thereby providing suitable reference points. Comparison of calibration data from the pre-run and data monitored during in-pile operation will give information on the cladding elongation.

Re-instrumentation / re-fabrication techniques

For high burn-up applications it is desirable to utilise standard light water reactor (LWR) fuel rods or segments pre-irradiated in a commercial reactor. Detailed performance assessments require that such rods be subjected to well controlled test conditions in a test reactor and that particular rod parameters be monitored on-line by means of suitable rod instrumentation which needs to be attached to the fuel rod before loading into the test reactor. The re-instrumentation sequence is illustrated in Figure 2.

A method for re-instrumenting an irradiated fuel rod with a bellows pressure transducer (PF) has been developed at the Project. After cutting, preferably in the plenum section, the rod is equipped with a new end plug containing the pressure sensing bellows with a magnetic core attached (also described in section entitled *Bellows Pressure Transducer (PF)*). After tungsten inert gas (TIG) welding of the end plug, the rod is dried and thereafter pressurised with pure dry helium gas and seal welded. A helium leak test completes the operation.

The main motivation for this type of measurement is to characterise the fission gas release at high burn-up in order to verify that end-of-life pressure criteria are met. Although the operating power at high burn-up is relatively low, the decreased fuel thermal conductivity and the presence of possible rim effects may contribute to gas release.

Another technique is being perfected at Halden for re-instrumenting previously irradiated fuel rods with fuel centre-line thermocouples (also described under *Fuel Centre-line Thermocouple (TF)*). This technique, originally developed at the Risø laboratories in Denmark, enables investigations on fuel thermal performance at high burn-up to be carried out without the need of long term irradiation in a test reactor.

The main motivation for this type of measurement is that during irradiation the fuel may undergo substantial changes in physical properties, e.g. reduction of conductivity and build-up of a pellet outer rim which may impair the fuel thermal performance.

The procedure for re-instrumenting a pre-irradiated fuel rod with a fuel centre-line thermocouple can be summarised as follows:

- Neutron radiography of the fuel rod in order to determine where the rod should be cut to enable positioning of the thermocouple hot junction in the centre of a pellet.

- Cutting of fuel rod to specified length and drilling / removal of fuel to allow installation of the end plugs. Grinding of canning tube inner and outer diameter to remove oxide and thereby facilitate welding of the end sleeve.

- Assembly of end pellet (Al_2O_3), steering system, plenum spring and end sleeve.

- Welding of end sleeve to cladding.

- Evacuating and re-filling of fuel rod chamber and fuel rod with liquid CO_2 (pressure 60 bar). Freezing of fuel pellets by filling outer volume of drilling cell with liquid N_2.

- Drilling of centre hole in the fuel stack. Due to the fragmented pellet structure of the high burn-up fuel, reinforcement of the inner wall of the thermocouple hole is necessary in order to avoid collapse once the CO_2 is removed. After drilling, a molybdenum tube, which is chemically compatible with the fuel, is inserted in the centre hole.

- Slow heating of the fuel rod to room temperature under pressure and de-pressurising. Out-gassing in vacuum at 300°C for 72 hours.

- Insertion of the centre-line thermocouple in the fuel stack.

- Welding of rod end plug. Evacuation and refilling of rod with inert gas three times including final pressurisation to specified pressure. Then seal welding.

- Helium leak testing of the complete fuel rod and verification of thermocouple integrity by loop measurements.

- Neutron radiography at orientations 0° and 90°.

Instrumentation for in-core materials testing

Since 1992, the Materials Testing programme at Halden has included in-pile investigations aimed at addressing Irradiation Assisted Stress Corrosion Cracking (IASCC), the materials degradation phenomenon that affects the structural integrity of core component materials such as stainless steels and nickel-base alloys. The main objective of the IASCC studies has been to evaluate the effects of the fundamental parameters stress, environment and microstructure on the crack growth behaviour of reactor internals materials in conditions representative of commercial Boiling Water Reactors (BWRs). The studies have in particular been aimed at evaluating the benefits of hydrogen additions in slowing crack growth in materials where cracking is occurring.

The investigations have utilised both Double Cantilever Beam (DCB) and Compact Tension (CT) crack growth specimens. The instrumented specimen types are illustrated in Figure 3. Both specimen types were instrumented for crack growth monitoring by means of the reversing direct current (DC) potential drop method. To date, three in-pile IASCC investigations [3,4] with instrumented crack growth sensors have successfully been conducted at Halden.

In the first investigation, a total of ten DCB specimens, eight of which were instrumented with internal probe attachments for on-line crack propagation monitoring, were utilised. The specimens, fabricated from common core component structural materials, were fatigue pre-cracked and wedge-loaded to a stress intensity of 37 $MPa\sqrt{m}$. During in-pile testing, crack growth rates were measured on DCBs fabricated from sensitised 304 SS both under Normal BWR Water Chemistry and with the addition of H2 to the loop water. The crack propagation monitoring enabled the benefits of H2 additions in slowing crack growth to be detected on-line while the investigation was in progress.

For the second investigation, which was a continuation of the first, selected DCBs were re-instrumented with external probe attachments for crack growth monitoring and transferred to a second rig for further in-pile testing. Results showed that the use of external probe attachments provided equally reliable in-pile crack growth data and during this study, the effectiveness of H2 additions in suppressing crack growth in materials with a radiation induced susceptibility to cracking, was demonstrated.

In the third investigation, two different fracture mechanics specimens, namely bellows-loaded DCBs and bellows-loaded CT specimens, are being utilised. Again, in the case of both specimen geometries, the DC potential drop technique is being employed to measure on-line crack propagation. The aim of this investigation has been primarily to evaluate the bellows loading concept as a means of varying applied stress intensity on-line during in-pile testing. In the case of both specimen types, variations in stress intensity resulted in corresponding changes in crack growth rate and the data have been found to compare favourably with both model predictions and literature data from laboratory studies. While the DC potential drop technique has often been utilised in out-of-pile studies at other laboratories, the in-pile data generated at Halden has clearly demonstrated that the technique can also be successfully applied in in-reactor environments and provides reliable real-time data on the cracking behaviour of DCB and CT crack growth sensors in a range of water chemistry environments and at different stress intensity levels.

REFERENCES

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[2] Stien, T.E., Instrument Calibration Data, Halden, August 1996.

[3] Karlsen, T.M., “Final Report on IFA-586/IFA-605: Effect of Water Chemistry on the In-pile Crack Growth Behaviour of Double Cantilever Beam Specimens,” HWR-473, Halden, April 1996.

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Figure 1. Linear Voltage Differential Transformer (LVDT)

In the figure below, the LVDT is shown in conjunction with a bellows mounted inside the fuel rod end plug. Together, the assembly constitutes the so-called bellows pressure transducer (PF).

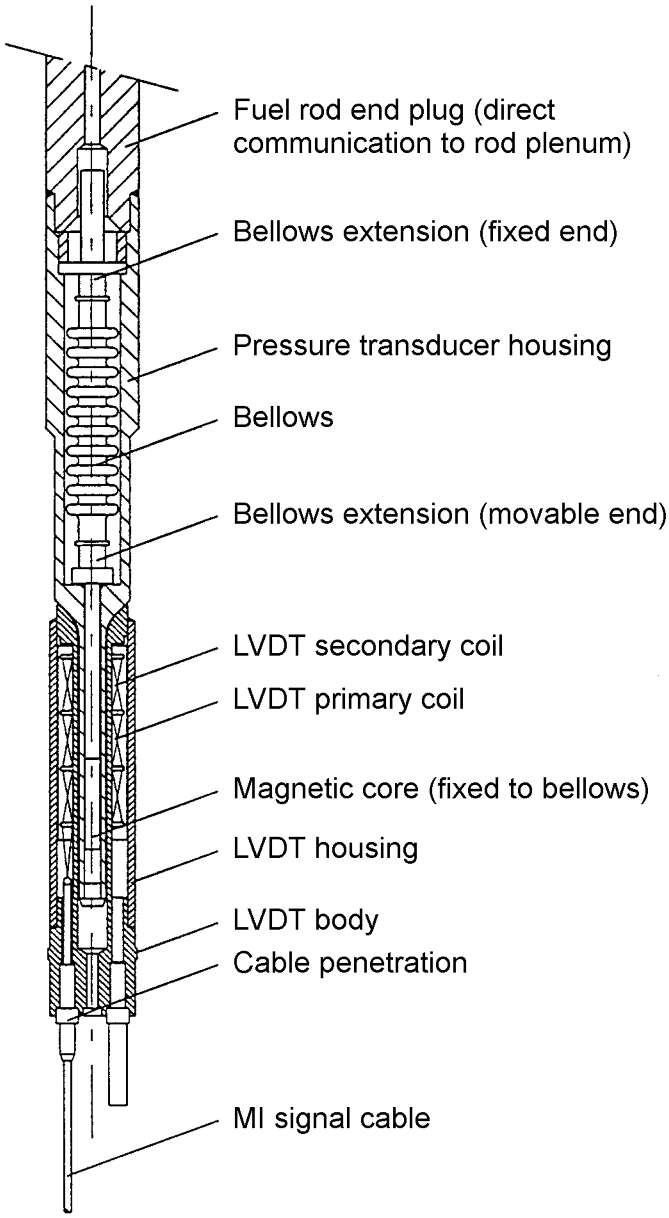
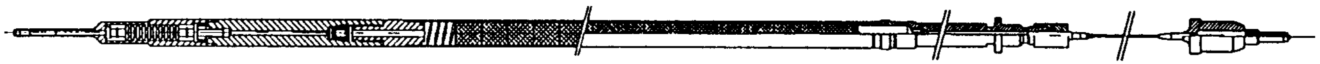


Figure 2. Re-instrumentation of pre-irradiated fuel rods

The figure below illustrates the re-instrumentation sequence, from the cutting of a segment from a full-length fuel rod to the completed rod equipped with bellows pressure transducer (PF) and fuel centre-line thermocouple (TF).

Fuel segment, cut from full-length rod and defuelled in both ends, with end sleeves welded into position and thermocouple hole drilled.

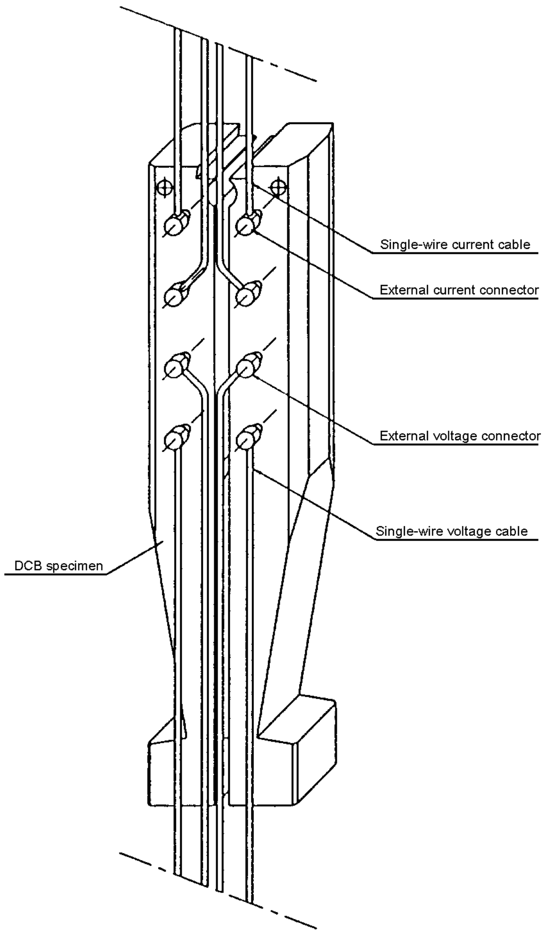
Pressure transducer welded into position.



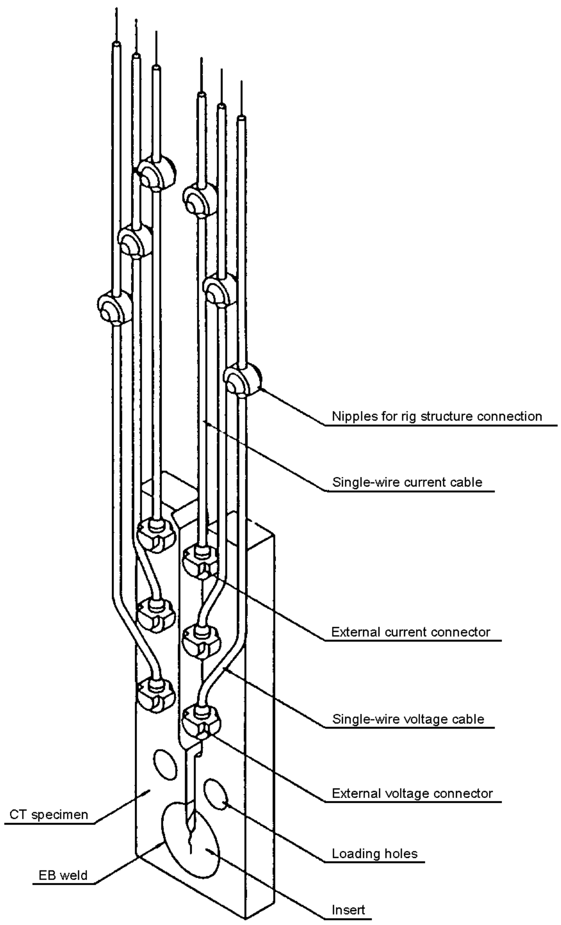
Fuel Thermocouple Assembly welded into position – finished fuel rod.

Figure 3. Specimens for material testing (IASCC)

The figure below shows two types of instrumented specimens (DCB and CT) utilised for IASCC testing at Halden.



Instrumented pre-irradiated DCB specimen



Instrumented CT specimen with pre-irradiated circular insert