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Overview of Fuel Testing Capabilities at the OECD Halden Reactor Project

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1 Introduction

The OECD Halden Reactor Project was established in 1958 as a joint undertaking of the OECD Nuclear Energy Agency through an agreement between nuclear centers of OECD countries sponsoring an experimental research program with the Halden Boiling Water Reactor (HBWR), which is owned and operated by the Institutt for Energiteknikk, Norway. Following the first agreement, eleven more have been entered into, the present one ending in December 1996. Some joint program and bilateral test plans reach well beyond that date already now and provide the starting point for further agreements. The reactor, which is continuously renewed and technically upgraded, has a life-time to beyond 2105, making it a reliable facility for execution of the most long-ranging test plans.

The early research programs were aimed at demonstrating the operability of HBWR type reactors and included extensive physics and dynamic studies. Then the emphasis gradually shifted to performance investigations on light water reactor fuels and materials and the development of computerized supervision and control systems. The main areas of activity defined in the present three years program from 1994-1996 are:

- high burnup fuel performance, safety and reliability;
- degradation of in-core materials and water chemistry effects;
- man-machine system research.

From the beginning, fuel performance and reliability investigations were supported by the development and perfection of in-core rod instruments. The measurement capabilities are expanded through development of experimental rig and loop systems where reactor fuel and material can be tested under light water reactor conditions, including prototypic PWR and BWR water chemistries.

It is believed that experimental studies and modeling of VVER fuel behavior can benefit from experience with western LWR fuel. In keeping with the theme of the seminar, the paper therefore gives an overview of testing capabilities and applications mainly aimed at exploring mechanisms of fuel behavior, also as related to high burnup. Examples of fuel performance are taken from data provided by the Halden Project for the IAEA Co-ordinated Research Program FUMEX (Fuel Modeling at EXtended burnup, [1]).

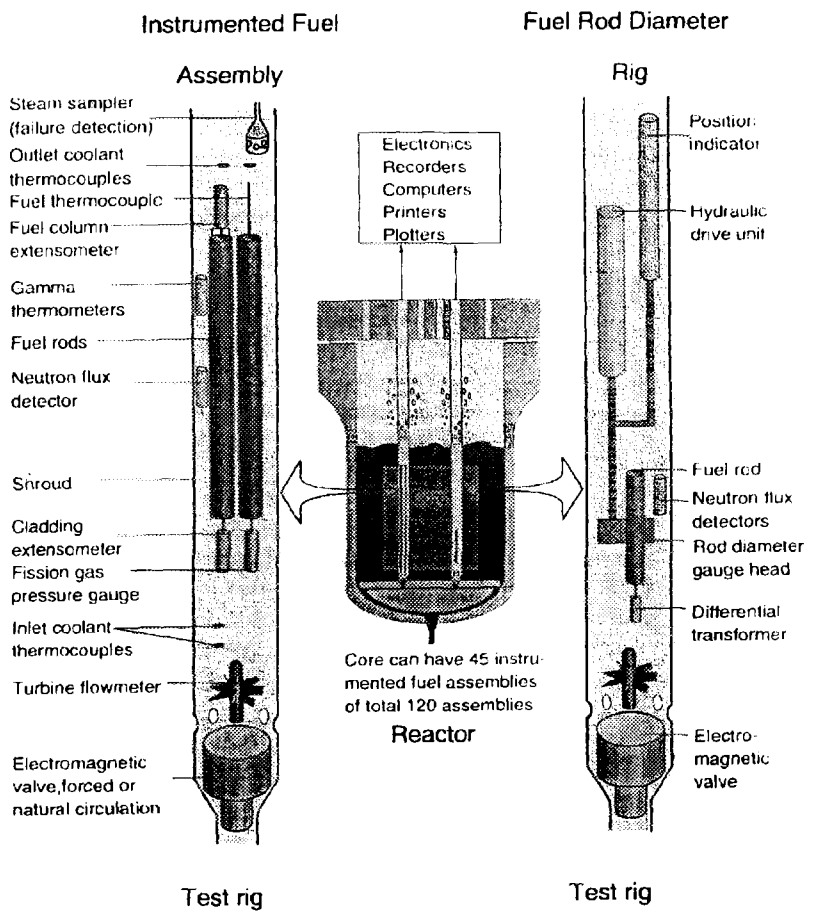

Figure 1 **Principal layout of HBWR with instumented fuel assemblies. HBWR: natural circulation boiling heavy water reactor with max. power of 25 MW; The ccolant water temper. is 240°C, corresponding to operating pressure of 33.6 bar.**

2 Instrumented Fuel Assemblies and Irradiation Rigs

An instrumented fuel assembly represents a test train in which one set of fuel rods can be tested, while irradiation rigs designate test hardware in which fuel rods are exchangeable. A number of heavily instrumented rigs to suit different test objectives have been developed. Some of them are illus-

trated in Fig. 1 and described below. Many other types of rig not further explained here have been utilized over the years. They are associated with testing of fuel from special reactors, e.g. advanced gas-cooled reactor, advanced thermal reactor. Also rigs for studies of LWR core component materials may be included in this category. In general, the Halden reactor provides versatile means to simulate conditions prevailing in planned and existing commercial nuclear power plants.

Base irradiation rig

As the name implies, this rig is used mainly for burnup accumulation prior to specific testing in other rigs. A control of rod power is provided through flow channel instrumentation (turbine, coolant thermocouples) and neutron flux measurements.

Gap meter rig

This rig allows the assessment of the fuel-to-cladding gap by squeezing the cladding onto the fuel, measuring force and deflection. Hot fuel expansion, relocation and swelling have been determined in this way in previous experimental periods.

Diameter measurement rig

In this rig, a diameter gauge can be moved along the fuel rod during operation. The change of cladding diameter in response to various modes of operation and burnup can be obtained with a micrometer precision.

Ramp rig

Ramps and overpower tests are effected in various ways: by moving rods from low to high flux positions during operation, using (movable) neutron absorption shields, depressuring coils with helium-3, or combinations of these. Also daily load following and frequency control modes of operation can be executed with these designs and have in fact been investigated.

Gas flow rig

This type of rig allows the exchange of fuel rod fill gas during operation. The gap thermal resistance and its influence on fuel temperature can thus be determined. It is also possible to analyze swept out fission products for assessment of fuel structure changes and fission gas release [2]. Further possibilities are indicated in section 4.4.

Instrumented fuel assembly

Designs differ largely with specific testing purposes and requirements. Rods can be heavily instrumented with thermocouples, pressure transducers and elongation detectors and stacked in several clusters. An example of a possible combination is shown in Fig. 2, which schematically depicts the arrangement and instrumentation of test rods for comparative testing of VVER fuel. The start of this experiment is foreseen for 1995 and the results will be available for the joint program of the Halden Project. The data are expected to provide information on fission gas release, thermal and mechanical behavior.

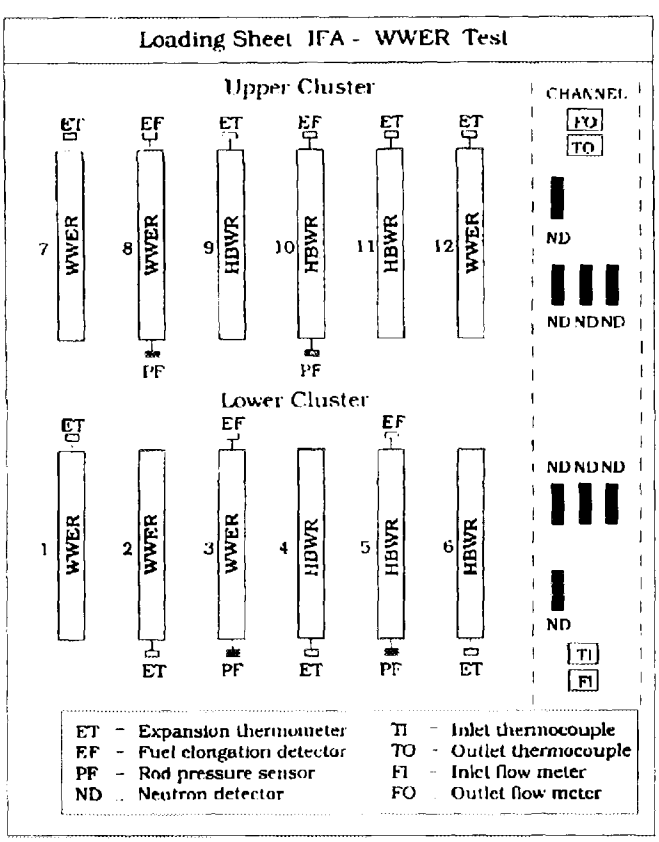

Figure 2 Layout of comparative test of VVER fuel. The instrumentation will provide data on thermal performance, fission gas release and fuel dimensional behaviour (swelling, densification)

3 Instrumentation Capabilities

While PIE ascertains the state existing at the end of irradiation, in-core instrumentation combined with expedient experimental techniques and test designs can give information on when and how phenomena occurred for the entire in-core service. Trends developing over several years, slow changes occurring on a scale of days or weeks and transients from seconds to some hours can be captured by the same instrumentation, altogether making up the total picture of fuel behavior.

The Halden Project has more than thirty years of experience in performing in-core measurements and a variety of sensors have been developed for this purpose. Most of them are designed and produced in-house, while a few - such as thermocouples and self-powered neutron detectors - are acquired commercially. They are typically applied in fuel performance investigations to obtain information on:

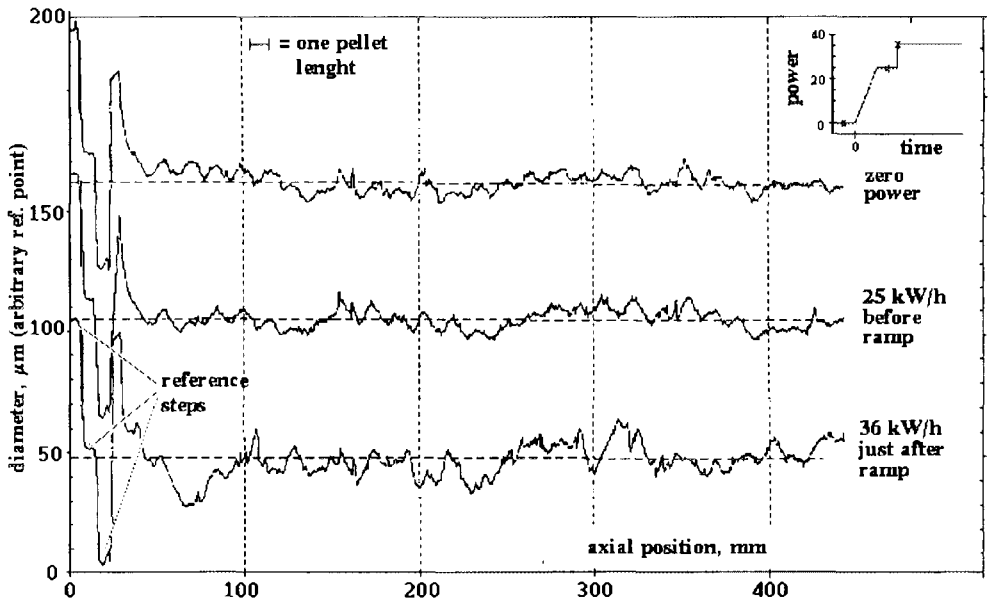

Figure 3 **Diameter traces obtained during ramp testing (FUMEX-5). Cladding diameter changes can be measured with high precision relative to calibration steps in the end plug (left side of figure)**

- fuel centre temperature and thermal property changes as function of burnup;
- fission gas release as function of power, operational mode and burnup;
- fuel swelling as affected by solid and gaseous fission products;
- pellet-cladding interaction manifested by axial and diametral deformations.

The following instruments are utilized for this purpose:

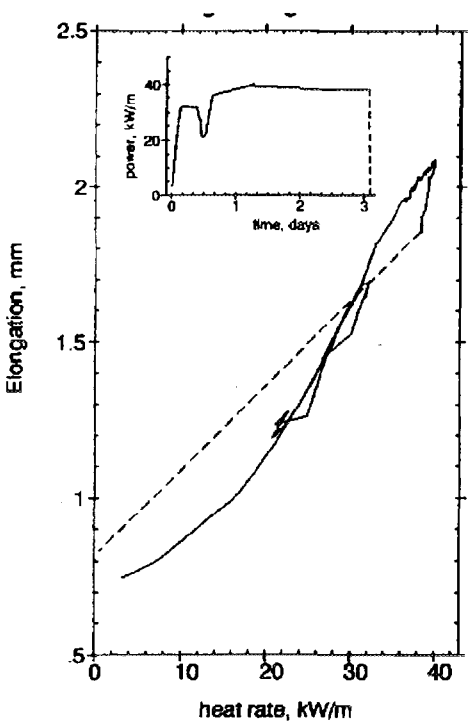

Figure 4 **Cladding elongation measured during power ramp and following holding period. The data indicate relaxation at power and permanent length increase**

- fuel thermocouples or expansion thermometers, which measure the fuel center temperature;
- bellows pressure transducers, which provide data on fission gas release by measuring the rod inner pressure;
- fuel stack elongation detectors, with which densification and swelling behavior can be assessed;
- cladding diameter gauge, with which radial deformation can be determined as function of power, holding time after ramping and burnup. Typical diameter traces are shown in Fig. 3 (FUMEX 5);
- cladding elongation detectors, which provide data on the onset and amount of pellet - cladding interaction, permanent deformation as well as relaxation capabilities of fuel and cladding as function of power and burnup (e.g. Fig. 4).

These instruments (with the exception of the fuel thermocouple and the diameter gauge) operate by means of a magnetic core inserted in a differential transformer (LVDT). Thus no cable penetration into the fuel rod is required and the fuel rods can be unloaded/reloaded without losing the measurement capabilities.

4 Rod Design and Irradiation Techniques

Investigations of fuel performance parameters, especially at high burnup, have to deal with a number of experimental problems, i.e. the time required for burnup accumulation, the demand of instrumentation to function reliably and the need for a separation of an increasing number of phenomena. The Halden Project has developed and applied techniques which make it possible to obtain reliable data for all relevant burnups, from beginning-of-life to ultra high exposure reaching 100 *MWd/kg* UO_2.

4.1 Design Features for Simulation of Burnup Effects

Increasing burnup in general incurs increasing uncertainties in data interpretation, e.g. fuel temperature changes can be effected by a combination of causes like fission gas release, changes in gap size (densification swelling, clad creep-down), and conductivity degradation. Test design with controlled and known influential parameters therefore facilitate the assessment of separate effects.

Fill Gas Composition

Fission gas release (an effect with considerable spread in model prediction) can be simulated by known additions of xenon to the fill gas. Fuel modeling codes must be able to predict the resulting change of the temperature-power relationship in a satisfactory manner. An example of the difference in fuel temperature caused by 8% and 23% xenon compared to pure helium fill gas is shown in Fig. 5 (FUMEX-4).

Small initial gap

Xenon fill gas in combination with a small as-fabricated gap (50 - 100 μm) simulates a high burnup situation (large amount of released fission gas, closed gap due to fuel swelling and clad creep-down) which is quite important for safety assessments. Gap conductance models cam be verified with measured data from tests with such a design without the uncertainties caused by high burnup. Examples of this can be found in the FUMEX-3 data set [1].

4.2 Fast Burnup Accumulation

Burnup representative of extended fuel cycle discharge values can be accumulated in an accelerated manner (about 20 *MWd/kg* UO_2 per year) by using highly enriched fuel and special geometries.

Small diameter rods

Thin rods (ca. 6 *mm* pellet diameter) are operated at a high fission rate per unit volume. Linear heat ratings and temperature profiles typical of LWR fuel can thus be obtained. Several such experiments are presently under irradiation in the HBWR. One has reached about 80 *MWd/kg* UO_2; its purpose is the investigation of fuel conductivity degradation and fission gas release at high burnup. Some results from the earlier stage of irradiation (up to 50 *MWd/kg* UO_2) were presented in [3].

Isothermal disks

This technique consist of an alternate series of fuel and molybdenum disks. The latter functions as an effective sink for the heat from the fuel disks. With a suitable gap between cladding and molybdenum disk and a proper choice of fill gas, the disk temperature can be selected independent of the specific power. In this way, it is possible to operate at very high fission density (fast burnup accumulation) while keeping the fuel temperature at low or moderate levels. The technique provides near isothermal conditions in the fuel disks which are very suitable as PIE specimens.

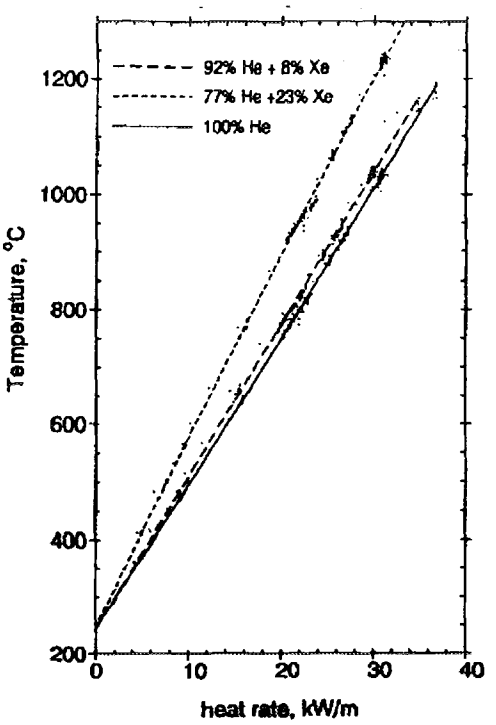

Figure 5 **Fuel temperatures obtained with different fill gaz compositions, simulating the effect of fission gas release**

4.3 Re-Instrumentation of Irradiated Segments

Re-instrumentation of fuel segments previously irradiated to high burnup has been used for several experiments. The sensors comprise pressure transducers, fuel thermocouples and cladding elongation detectors. Re-instrumentation with the latter is especially simple since it only requires the external fitting of a magnetic core to the segment, while the other two involve more elaborate techniques:

Pressure transducers

An instrumental head containing a bellows pressure transducer and a drill is welded onto the end plug of an irradiated rod. The reaction of the bellows to pressure changes in the fuel rod is picked up during further irradiation with an LVDT (linear variable differential transformer). Continuous measurements of the internal gas pressure give precise information about the fission gas release as a function of time and burnup. This is shown in Fig. 6 (FUMEX-6) where the onset of fission gas release is clearly detected.

Fuel thermocouples

Re-instrumentation of irradiated fuel rods with fuel thermocouples is part of the current Halden Project program. The technique, based on Riso experience, is fully implemented in the hot cell if Institutt for Energiteknikk at Kjeller, Norway and is applied to joint program and bilateral tests.

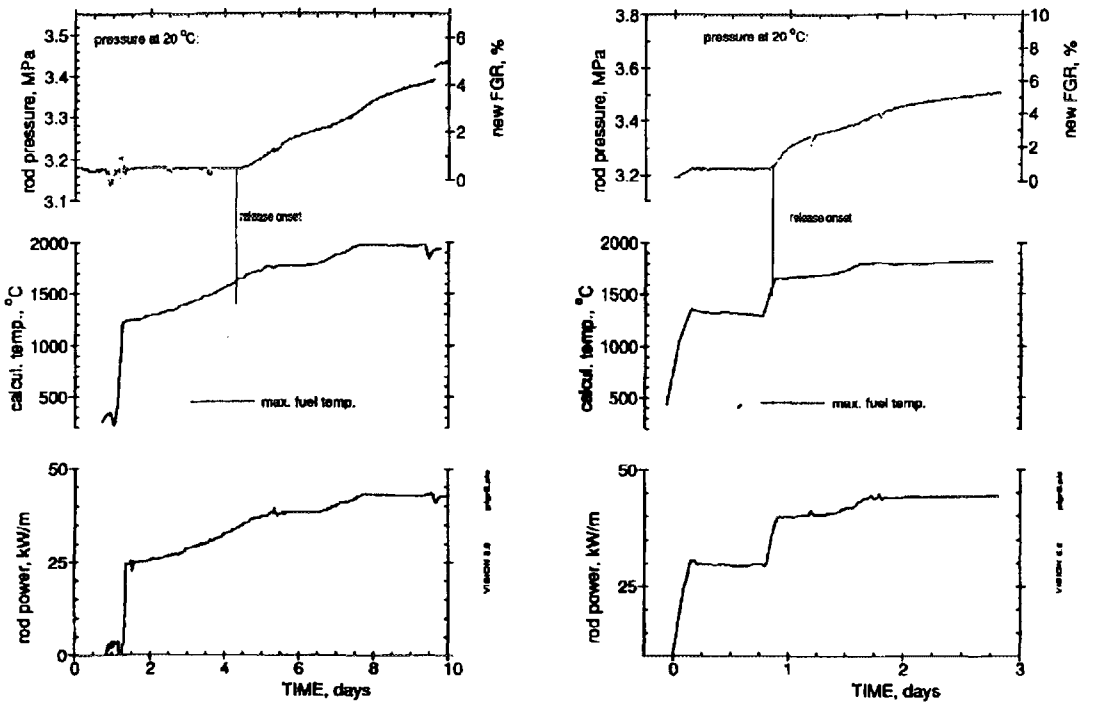

Figure 6 **Examples of pressure response (fission gas release) to slow and fast power ramps (FUMEX-6). The rods were re-instrumented with pressure transducers after base irradiation. The onset of fission gas release is clearly detected and occurs at about the same power in both cases.**

4.4 Experiments to Study Separate Effects

Most phenomena occurring in fuel rods during irradiation are interrelated, in particular via the influence of temperature. The dependencies tend to become more complex with burnup, while uncertainties increase. The possibility to study some effects separately or in relative isolation is therefore of great advantage for fuel performance modeling. Of particular relevance for thermal properties and fission gas release investigations are the Halden Project's gas flow rigs. In these rigs, the gas contained in the fuel rods can be changed and the pressure can be varied. Volatile fission products can be swept out, cold trapped and analyzed. With this type of rig, a number of parameters can be addressed:

Gap size

The hydraulic diameter or gap can be determined from the resistance that the fuel stack offers against the gas flow driven by a given differential pressure between the ends of a rod. Gradual gap closure with increasing burnup has been verified by this method.

Effect of pressure on temperature

The pressure and gas-type dependent temperature jump distance is an important parameter in fuel temperature calculation models. Variation of the fill gas pressure at constant power has an influence on the fuel centre temperature measured simultaneously. This effect (decreasing temperature with increasing pressure) is more pronounced for helium than for argon or xenon and increases with burnup - probably due to structural changes which create a growing of surfaces where the effect can take place.

Gas composition in the fuel-cladding gap

By changing the gas in a rod, the separate effects of several parameters can be investigated. For fission gas release, the influence of temperature can be assessed while keeping the power density constant, thus separating thermal and athermal release. It is also possible to determine the influences of fuel vs. gap heat conductance since mostly the latter is changed when replacing the gas filling, e.g. helium with argon.

Sweeping out and analysis of fission products

Volatile fission products swept out with the purging cover gas can be cold-trapped and analyzed using on-line gamma-ray spectrometry. The method allows the determination of release-to-birth ratios which are controlled by thermal and athermal diffusion processes. By analyzing the release rates of several short-lived isotopes it is possible to assess the surface-to-volume ratio which is a sensitive indicator of grain boundary porosity interlinkage and resintering [2].

4.5 Noise Analysis and Utilization of Transient Data

The technique of noise analysis is being used, in particular in conjunction with fuel thermal data, to monitor long-term changes which have an influence on fuel temperatures. These are essentially gap closure, fission gas release and conductivity changes which influence the time constant of the fuel. Also transient temperature data, obtained with

a recording system automatically activated during scrams, can be used to infer response (time constant) changes with burnup. These techniques have the advantage of being independent of the exact power and temperature. They provide supplementary information to steady state analyses and usually corroborate the results obtained therefrom. An example of scram data evaluation is shown in Fig. 7 (FUMEX-4). The time constant changed at 17 *Mwd/kg* UO_2 in response to fission gas release caused by operation at higher powers and temperatures than before.

5 Summary

Fuel performance and reliability investigations at the OECD Halden Reactor Project are supported by a variety of irradiation rigs, suitable irradiation techniques and a range of instrumentation. They have been perfected and applied over the years to assess separate effects as well as integral fuel behavior. Rod instrumentation (fuel thermocouples, bellows pressure transducer, cladding and fuel elongation detector) can also be attached to segments pre-irradiated in commercial LWRs, especially for high burnup behavior and fuel failure studies.

References

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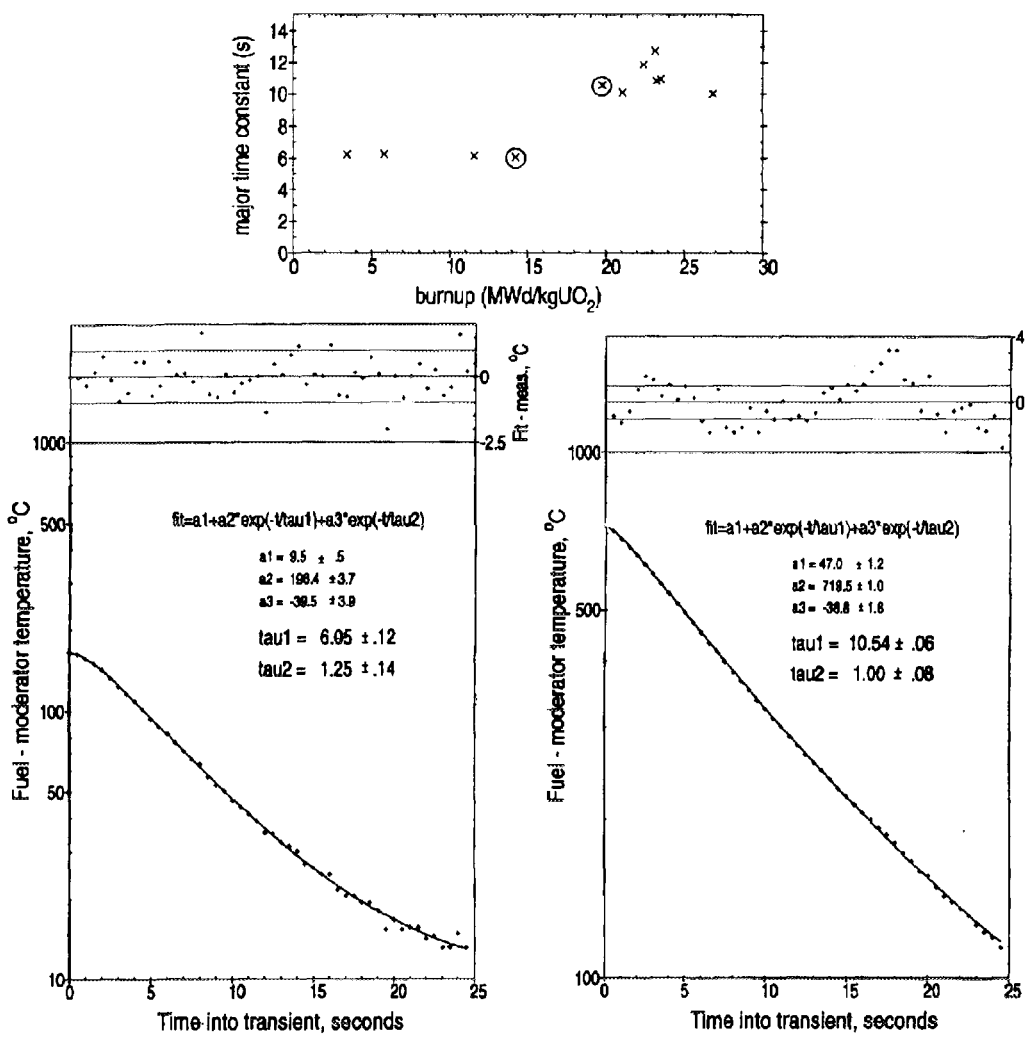

Figure 7 **Transient fuel temperature response after reactor scram. The fuel time constant is a measure of stored heat dissipation capability. Fission gas release occured during operation following the scram at 14.5 MWd/kg, and the time constant increased.**