PRELIMINARY RESULTS OF THE BTF-105B EXPERIMENT: AN IN-REACTOR TEST OF FUEL BEHAVIOUR AND FISSION-PRODUCT RELEASE AND TRANSPORT UNDER LOCA/LOECC CONDITIONS

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ABSTRACT

The BTF-105B test is one of a series of in-reactor, all-effects, tests performed to measure fuel behaviour, fission-product release, and transport from nuclear fuel subjected to accident conditions. The primary objective of the BTF-105B test was to determine the timing, amount, and transport characteristics of fission products released from a previously irradiated CANDU-sized fuel element subjected to a high-temperature transient, representative of a loss-of-coolant accident with loss-of emergency-core-cooling conditions, at an average fuel temperature of 1800°C. The preliminary results of the BTF-105B test are presented in this paper. The results include process parameters, from which boundary conditions could be derived for simulating the test; fuel parameters, such as sheath temperatures and hydrogen production rate; and fission-product release and transport data.

1. INTRODUCTION

The Blowdown Test Facility (BTF) is located in the National Research Universal (NRU) reactor at the Chalk River Laboratories of AECL. The objective of the BTF experimental program is to obtain data on fuel and fission-product behaviour from in-reactor, all-effects tests under conditions representative of loss-of-coolant accidents (LOCAs) for benchmarking computer codes used in CANDU safety and licensing analyses. The BTF-104 experiment was conducted under conditions representative of a LOCA with additional Loss-Of-Emergency-Core-Cooling (LOECC).[1] The BTF-105 experiment was similar but was divided into two tests: BTF-105A and BTF-105B. For BTF-105A an unirradiated fuel element was instrumented with two fuel-centreline thermocouples and then irradiated and tested.[2]

The primary objective of the BTF-105B test was to determine the timing, amount, and transport characteristics of fission products released from a previously irradiated CANDU-sized fuel element subjected to a high-temperature transient representative of a LOCA with LOECC. The BTF-105B test used a previously irradiated fuel element. One of the primary considerations in choosing the test conditions was to ensure that the data on fuel performance were well quantified. As a result, the target volume-average fuel temperature for BTF-105B was chosen to be about 1800°C for 15 minutes. This was expected to prevent gross damage and significant relocation of the fuel. The extended time at high temperatures is the main feature that distinguishes the BTF-105B test profile from the BTF-104 test profile. Also, the test conditions were much better quantified due to improvements in the measurement of fuel-sheath temperatures and the

measurement of flow over the fuel element. Another improvement for BTF-105B was that condensation in the test section was reduced and better controlled than in previous tests. This provided much more stable flow conditions during the test. Preliminary results of the BTF-105B test are presented in this paper.

2. FUEL ASSEMBLY

Figure 1 shows a cross-sectional view of the BTF-105B fuel assembly and its instrumentation. The fuel assembly consisted of a single Bruce-sized CANDU fuel element. The element was fuelled with UO_2 pellets, initially enriched to 4.99 wt% ^{235}U in total U, and sheathed with Zircaloy-4. The fuel element was previously irradiated to a burnup of 150 MWh/kg U. It was located inside a thermal shroud consisting of a NILCRA (100% dense ZrO_2) inner liner and a Zircaloy-4 clad ZIRCAR (21% dense ZrO_2) outer layer. The shroud protects the test-section pressure tube by insulating it from the high-temperature fuel. The fuel assembly and pressure tube are heavily instrumented with thermocouples and flux detectors (prefix T and R respectively in Figure 1).

3. TEST SEQUENCE

Figure 2 shows a schematic representation of the NRU reactor and BTF facility. Test assemblies in the BTF are cooled with pressurized water or saturated steam provided by the U-1 loop. An accident sequence test is initiated by isolating the BTF in-reactor test section from the U-1 loop, and voiding the coolant in the test section through an instrumented piping system (blowdown line) into a sealed tank (blowdown tank). Instrumentation on the blowdown line and tank consists of 12 gamma spectrometers, two oxygen sensors, an aerosol sampling system consisting of two thimble filters and two cascade impactors, 14 "U-tube" grab samplers for taking samples of the coolant and a mass spectrometer for analysing the coolant gas collected in the blowdown tank.

The BTF-105B fuel assembly was re-irradiated for about 15 days prior to the transient at a fuel-element linear power of about 55 kW/m under pressurized water cooling conditions to reestablish a representative inventory of fission products with short half lives. Four hours before the transient, the coolant was changed to saturated steam to simplify the thermalhydraulics of the blowdown. The total fuel burnup was about 170 MWh/kg U prior to the transient.

To start the transient, the reactor power was reduced to 2% of full power. About 5 minutes after the power reduction, the blowdown (depressurization) sequence was initiated. When the coolant pressure reached 0.5 MPa, a low flow of steam (about 5 g/s) was established to cool the fuel element during the high-temperature transient. The reactor power was increased in steps from 2 to 17% of full power (see the neutron flux in Figure 3). The transient was terminated, as planned, by shutting down the reactor about 15 minutes after reaching the high-temperature plateau.

4. PROCESS PARAMETERS

Figure 3 shows the neutron flux measured in the thermal shroud with a rhodium self-powered flux detector. The flux detector data have been corrected to improve the time response of the signal. This provides a local measurement of the thermal flux which can be used to give the fuel-element power. It varies somewhat from the reactor power because it captures local perturbations of the flux caused by movement of control rods with the reactor being held at a fixed total power.

Two turbine flowmeters and a cross-correlation flowmeter were provided to measure the coolant flow over the fuel element. The cross-correlation flowmeter works by measuring the transit time

of thermal noise between two thermocouples separated by a known distance. One of the turbine flowmeters stopped working before the transient and the other stopped working part way through the transient. The cross-correlation flowmeter only works well at high temperatures, when the thermal noise has a significant amplitude. Figure 4 shows measurements of the coolant flow over the fuel element. Although neither the turbine flowmeter nor the cross-correlation flowmeter provided good data throughout the whole transient, together they provide enough data to cover the transient with a small overlap when the two instruments both provide data.

Coolant temperatures measured above and below the fuel element during the transient are shown in Figure 5. The coolant temperature above the fuel generally increases throughout the transient starting at about 280°C and reaching a peak of about 410°C. Likewise the coolant temperature measured below the fuel generally increases from about 310°C to about 1050°C. These temperature data have several rapid decreases between 2400 and 3200 s. These "spikes" are a result of short increases in flow caused by the use of the blowdown line coolant sampling U-tubes. The coolant temperature rise across the fuel (TC08B-TC06T) is shown in Figure 6.

Measurements of additional process parameters such as thermal-shroud and pressure-tube temperatures, coolant pressures, pressure-tube neutron-flux, and blowdown line and tank gamma-radiation fields were obtained during the test.

5. FUEL PARAMETERS

Figure 7 shows fuel-sheath-thermocouple temperatures measured at bearing pad locations near the top, middle and bottom of the fuel element. The thermocouples are attached to the sheath through the use of robust clamps. Convective cooling of these clamps causes the thermocouple to read a temperature which is lower than the actual sheath temperature under the thermocouple which in turn is cooler than adjacent regions of the sheath. For example, at the peak of the transient, it is estimated that the TFS03 thermocouple, at the lower bearing-pad position, was reading 170°C lower than the sheath at this location, and 400°C lower than the hottest sheath location. Data from out-reactor experiments have been used to develop a model to relate thermocouple readings to actual sheath temperatures.[3] When this model is incorporated in the CATHENA code it is possible to calculate the sheath temperature near the bottom of the fuel element where the hottest fuel-sheath temperatures are expected. Correlations derived from a CATHENA calculation were used to estimate fuel-sheath temperatures at the bottom of the fuel element corresponding to the measured values of TFS03, as shown in Figure 3.

Figure 8 shows measured top end-cap temperatures. These are measured by thermocouples which are embedded in holes drilled into the end cap. Because they are located at positions within the end cap they are not subject to finning losses. The two thermocouples are located 1 cm apart and the measurements indicate that there is a significant temperature gradient along the end cap.

Fuel element failure was detected at 2460 s by the gamma monitors on the blowdown line during the plateau at 7% of full power. At this time (see Figure 3) the maximum fuel-sheath temperature is estimated to have been 900°C.

6. HYDROGEN DATA

During the transient, hydrogen production was monitored by two oxygen sensors, located in the blowdown line and the aerosol system bypass line. Also, during the transient, a mass spectrometer measured the concentration of hydrogen in the blowdown tank. Figure 9 shows hydrogen production rates determined from the oxygen sensor measurements. Data from the two

oxygen sensors are in good agreement except at the beginning of the transient when the blowdown line oxygen sensor was not operational and after the transient where there is some difference between the two oxygen sensors. Integrating the data from the oxygen sensors indicates that about 1 g (about 10 L at STP) of hydrogen was produced during the transient. This is in agreement with the concentration of hydrogen in the blowdown tank immediately after the transient as measured with the mass spectrometer.

7. FISSION-PRODUCT DATA

Ten of the twelve gamma-spectrometers collected data on-line during the BTF-105B transient. The spectrometers labeled "TS" and "BDL" in Figure 2 did not have the benefit of the reactor lower biological shield and were saturated throughout the test. During the transient, the "Trench" spectrometer was positioned on the blowdown line, upstream of the grab-sample tubes. The tank side-stream was sampling from the tank liquid, while the tank spectrometer was positioned to view the vapour space. Spectrometers NW2, NW4, and NW6 were fitted with computer controlled sliding-wedge collimators that were adjusted to control the count rate. Also under computer control, the distances from the BF and AF spectrometers to the blowdown line were adjusted to optimize the count rate. Without the advantage of variable sensitivity, spectrometers NW3 and NW7 saturated shortly after fuel failure.

Gamma emissions from Xe, Kr, Rb, I, Cs and Te isotopes were detected. The noble gases (^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{129m}Xe, ^{133}Xe and ^{135}Xe) were detected immediately following element failure and during power ramps from 7% to 9% and from 9% to 13% of full power. This can be seen in Figure 10 where the noble gas activities at NW4 are plotted along with the bottom sheath-thermocouple temperature, TFS03. The time periods marked as "data gap" in Figure 10 and Figure 12 are the result of a software deficiency that necessitated the restarting of the data acquisition computers every half-hour. Later in the test, the noble gases were difficult to detect in the blowdown line because of the high background from deposited iodine isotopes. One-second duration grab-samples taken from the blowdown line, about 20 m downstream from the fuel element, permitted the observation of the noble gases without the build-up of iodines. For example, in Figure 11 the isotope activities observed by the "Trench" spectrometer are plotted, for the morning following the transient. Note that at the blowdown line, which was exposed to continuous flow, only iodines and the parent tellurium are detected. (The ^{135}Xe observed is the decay-product of ^{135}I.) At the grab samples, the only iodine observed is ^{133}I, and it is more than three orders of magnitude less active than that in the blowdown line. The first grab sample (U1) was taken during the initial burst of noble gas release. (The "L" and "B" suffices on the plot labels denote Left and Bottom positions on the "U" shaped sample-tubes.) ^{88}Kr and ^{88}Rb are seen in this sample (U1) along with the other noble gases, but are not detected elsewhere. The second-most active sample is U6, which corresponds to the power ramp from 7% to 9% full power.

Iodine (^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I) was also detected at the time of element failure. The iodine signals increased exponentially as shown in Figure 12 as the iodine deposited on the blowdown line. No spiking was seen in the iodine activities, even during power ramps, including reactor shutdown. The ^{138}Cs emission pattern was similar to that of the iodine isotopes.

The noble gases dissolved in the blowdown tank liquid were measured at the recirculating side-stream. As can be seen in Figure 13, the integrated release is consistent with the large initial burst detected at the other spectrometers. The majority of the total noble-gas release occurred within 5 minutes of fuel failure. The short-lived (18 minutes) decay-product of ^{88}Kr, ^{88}Rb (also shown in Figure 13), approaches the activity of ^{88}Kr, suggesting that the side-stream sampling process has reached equilibrium. Figure 14 presents the iodine and cesium activities observed at the same location and over the same time period. Although the mixing in the tank and deposition

along the sampling line had not reached equilibrium, the relative activities of the isotopes are consistent with that seen at the upstream spectrometers.

Over the month following the transient, gamma-ray spectra of the liquid and vapour in the blowdown tank were measured using the side-stream and by directly viewing through the wall of the tank. An example of the activities observed during a vertical scan of the blowdown tank is given in Figure 15. When this scan was taken, the noble gases had collected in the vapour space and the iodines were concentrated in the liquid. An exception is ^{135}Xe which is found only in the liquid as the decay product of ^{135}I.

Thirty-eight days following the transient, the cascade impactor tray-liners and the thimble filters from the two aerosol-collection systems were gamma-counted. The gamma activities on the first set of tray-liners are plotted in Figure 16. In both sets of liners, the majority of activity was at either end of the tray stack, with the activity at the mid-point being 10 to 100 times less than that at the ends. This indicates that a large fraction of the activity was from structural material (possibly fuel particles) and a roughly equivalent fraction was from aerosols that were less than 1 μm in diameter. The activities observed on the two thimble filters are plotted in Figure 17. The mix of isotopes is generally the same in both filters. While the second filter shows less activity, it was exposed for a shorter duration than the first filter. The average rate of deposition on the second filter was greater than that on the first filter. Activities similar in amplitude and similar in isotope ratios were found on the blowdown line filter.

Six deposition coupons of seven different materials were suspended at six elevations in the blowdown tank, spanning the liquid and vapour regions. Coupon activities, averaged by material, are shown in Figure 18. Relative gamma activities are similar to that seen in BTF-104, where the depositions of tellurium and iodine were an order of magnitude greater on the A106 carbon steel and 403 stainless steel, than were observed on Zr 2.5% Nb or Zircaloy-4.

The blowdown line was flushed with cold water after the fuel assembly was removed from the reactor core. Fission-product deposition data were collected both before and after the water flush. Similar to observations from BTF-104, iodine (^{131}I, and ^{133}I) and cesium (^{137}Cs) were removed from the blowdown line piping (Type 347 Stainless Steel) with about 90% efficiency by the water flush. The removal efficiency was about 50% for ^{132}Te. At 15% efficiency, the removal of ^{140}La was only one-third as effective compared to BTF-104.

8. POST-IRRADIATION EXAMINATION

The BTF-105B fuel assembly was gamma scanned in the reactor building before it was potted in epoxy and then again, prior to disassembly, to confirm that the injection of epoxy had not relocated the active material. The epoxied fuel assembly was cut into several sections to facilitate gamma scanning of the fuel, debris retainer, deposition quadrants, and other stringer components. Gamma scans, performed after the transient, showed uniform activity over the element length with the exception of a 20% drop over a 1 cm section near the bottom of the fuel stack, as can be seen in the ^{95}Nb and ^{103}Ru activities plotted in Figure 19. This is in agreement with a digital radiograph of the fuel element (also shown in Figure 19) which shows that most of the fuel damage occurred near the bottom of the element. ^{140}La was detected in the debris retainer below the fuel element indicating the presence of small amounts of fuel material.

In Figure 20 ^{131}I and ^{137}Cs activities are plotted versus longitudinal position. Note the correlation between the location of activity peaks and that of the clamps used to hold thermocouples on the sheath. The fin cooling provided by the clamps has had significant impact on the migration and precipitation of iodine and cesium, particularly over the lower (hotter) length of the element.

9. CONCLUSIONS

Due to improved fuel-sheath temperature, flow and neutron flux measurements, and better control of test section condensation, the thermalhydraulic boundary conditions for the BTF-105B test are better quantified than for previous LOCA/LOECC tests performed in the blowdown test facility. Hydrogen-production and fission-product data were obtained during the transient. Gamma scans and gamma radiography indicate that the majority of fuel element damage is constrained to a region near the bottom of the fuel element. In the future, cross-sectional gamma-scans, and metallography will be performed on the fuel element to measure fuel sheath oxidation and the microstructure of the fuel and fuel sheath.

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(3) L.C. Walters, J.W. DeVaal and N.K. Popov, "Development of a Model for Calculating Sheath Thermocouple Finning Losses for Application in In-Reactor Severe Fuel Damage Tests," presented at the Canadian Nuclear Society 20th Simulation Symposium, Niagara-on-the-Lake, Ontario, Canada, 1997 September 7-9.

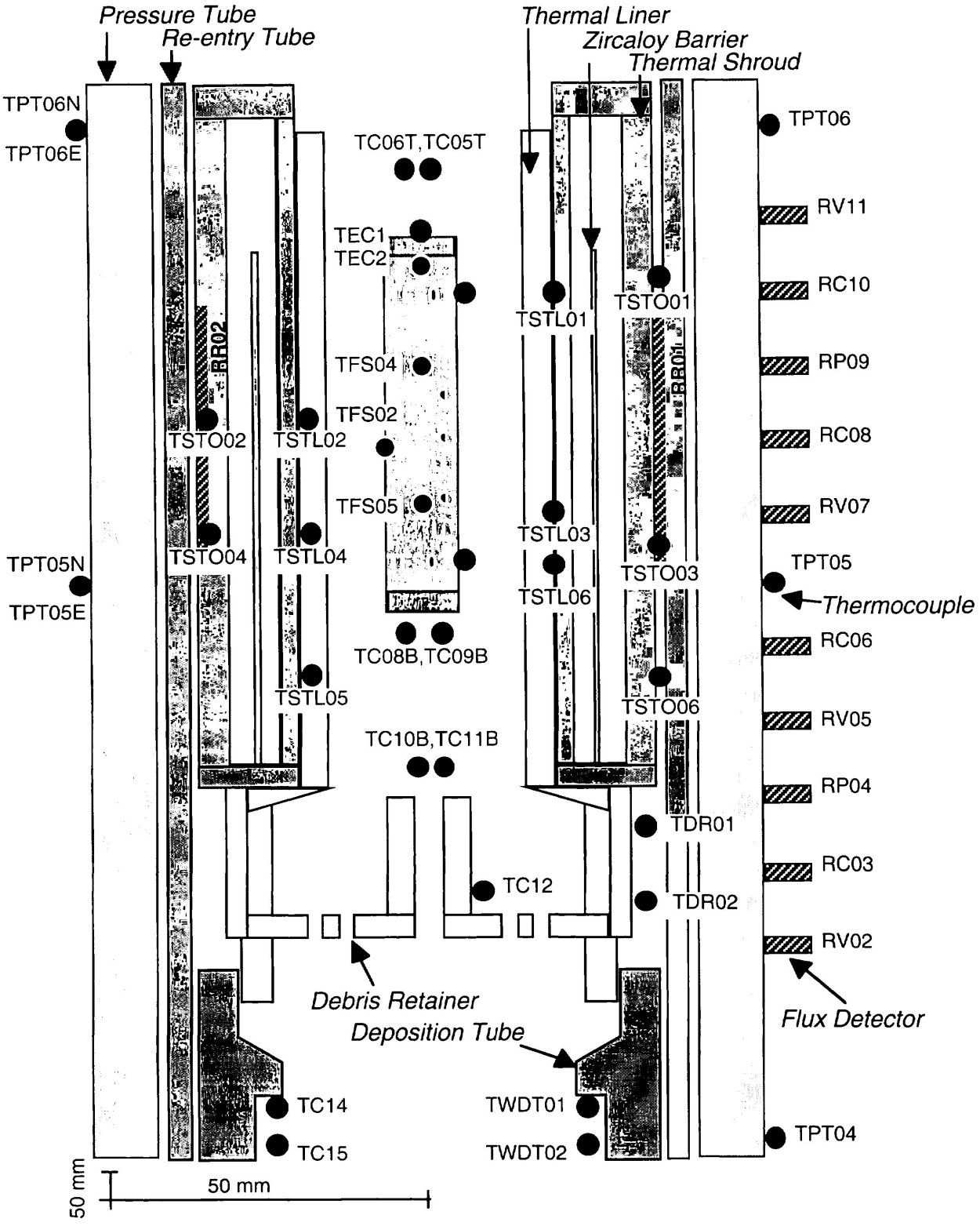

Figure 1: *Cross-Sectional View of BTF-105B Fuel Assembly and its Instrumentation*

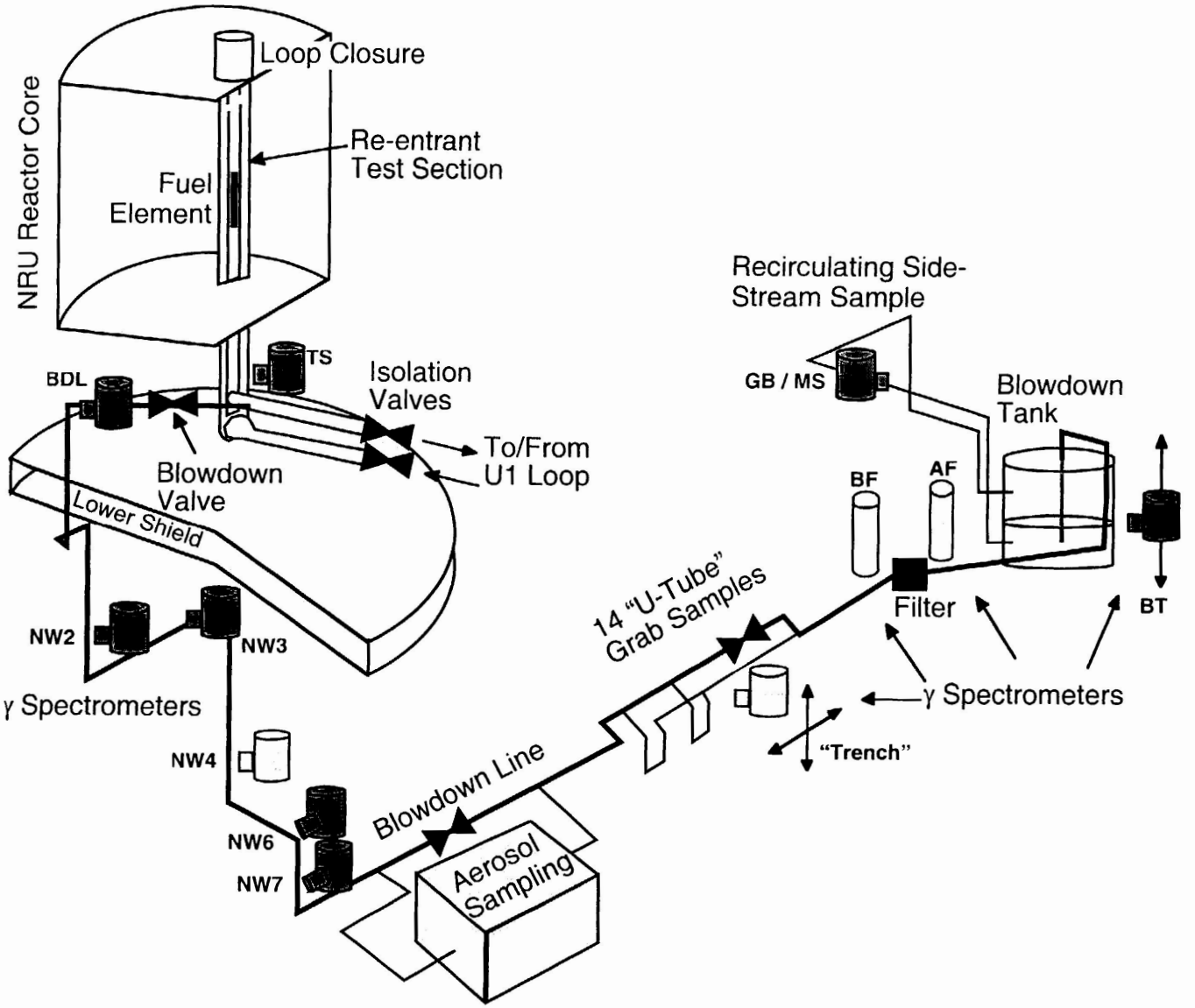

Figure 2: *NRU Reactor and BTF*

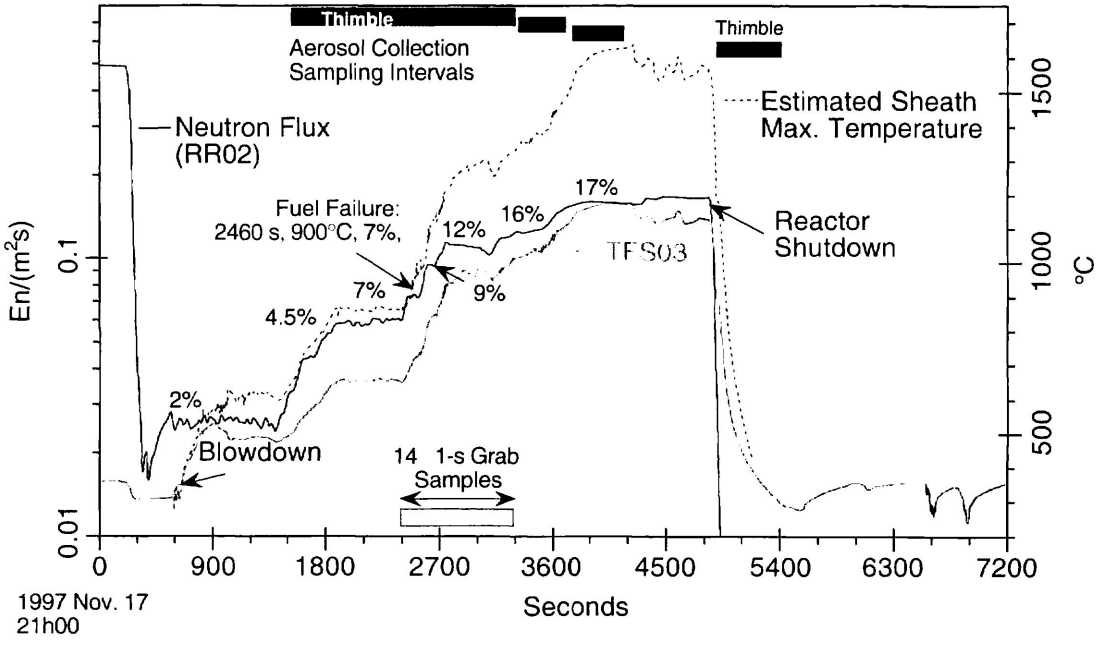

Figure 3: *Neutron Flux and Sheath Thermocouple Temperature*

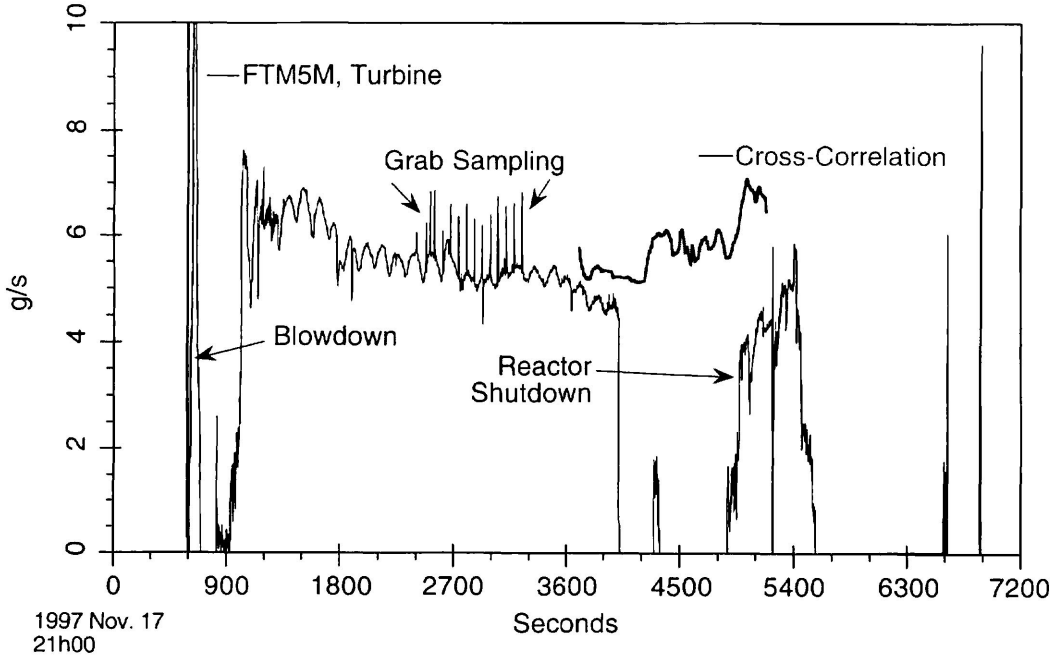

Figure 4: *Coolant Flow Over Fuel*

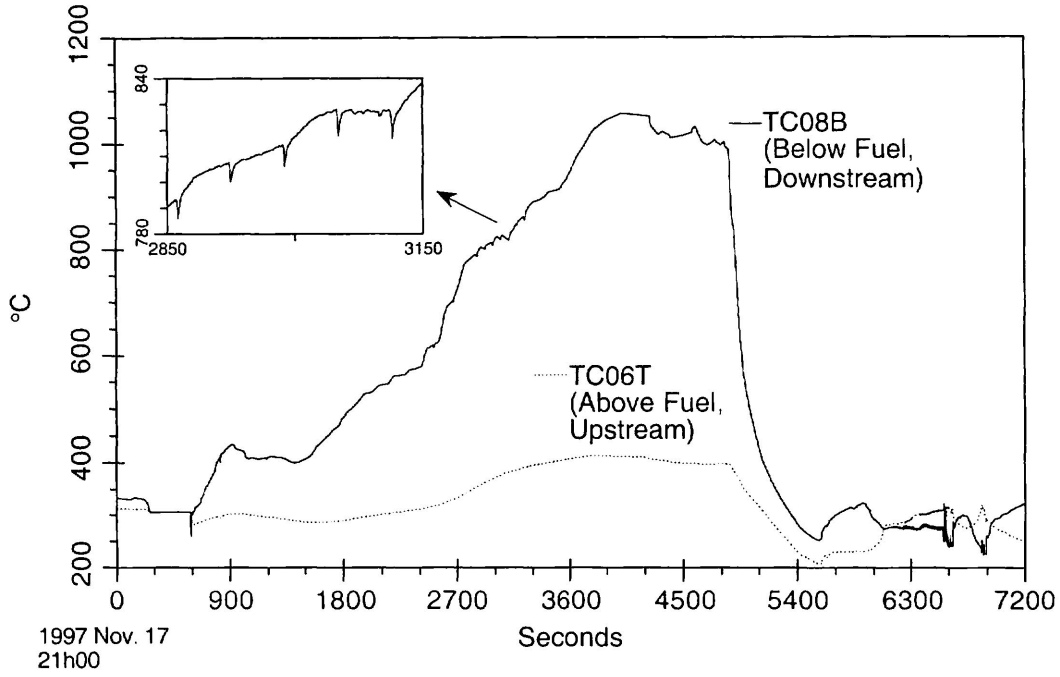

Figure 5: *Coolant Temperatures Above and Below Fuel*

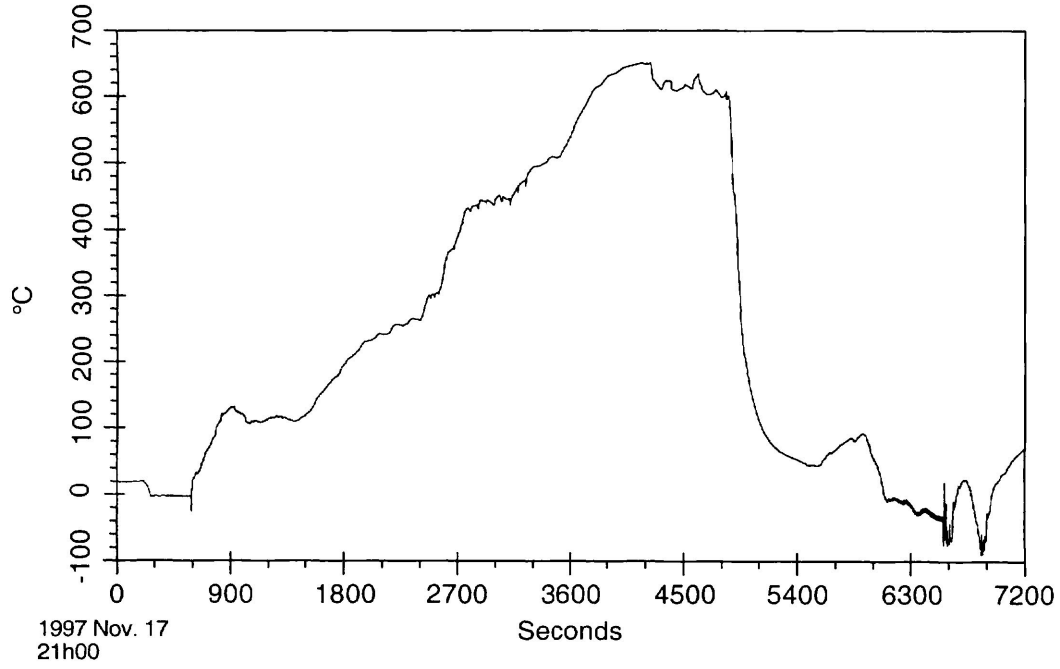

Figure 6: *Coolant Temperature Rise Across Fuel (TC08B - TC06T)*

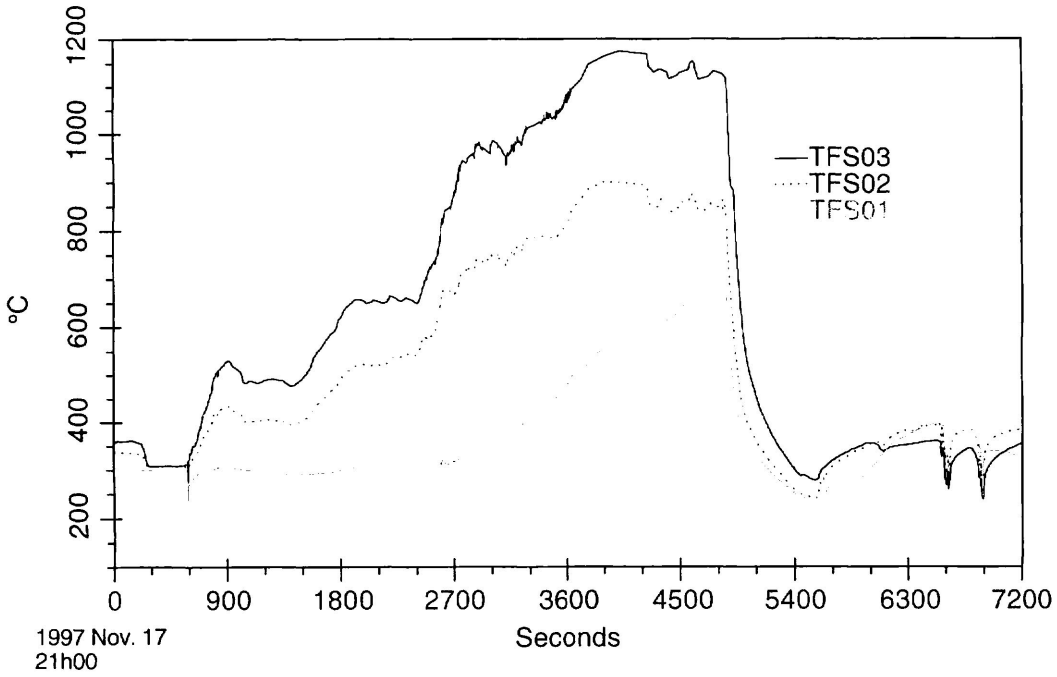

Figure 7: *Fuel-Sheath-Thermocouple Temperatures*

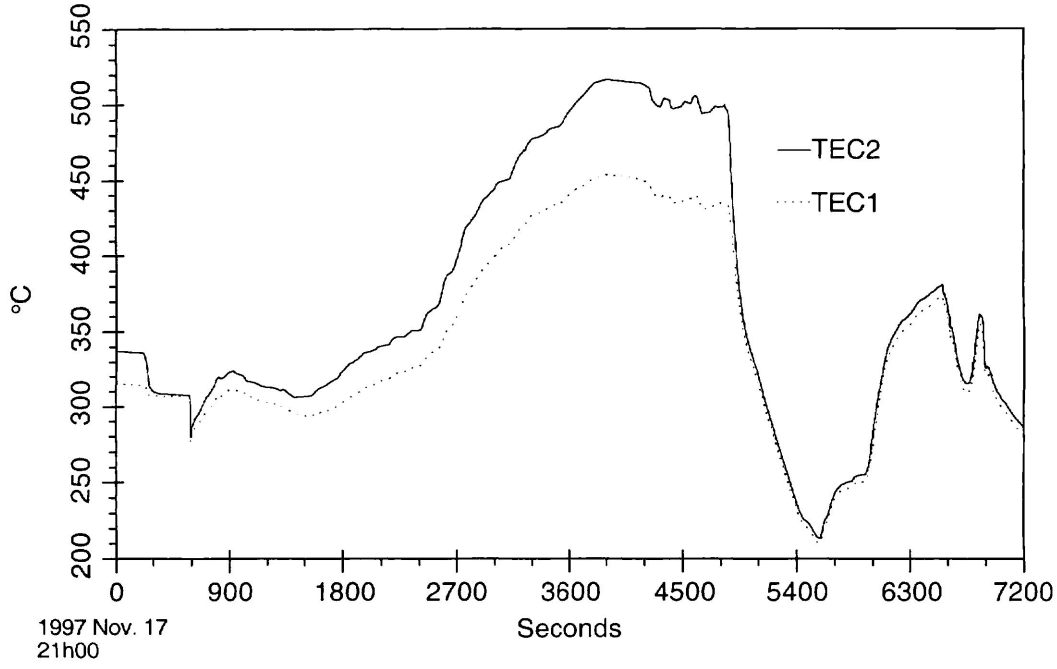

Figure 8: *End-Cap Temperatures*

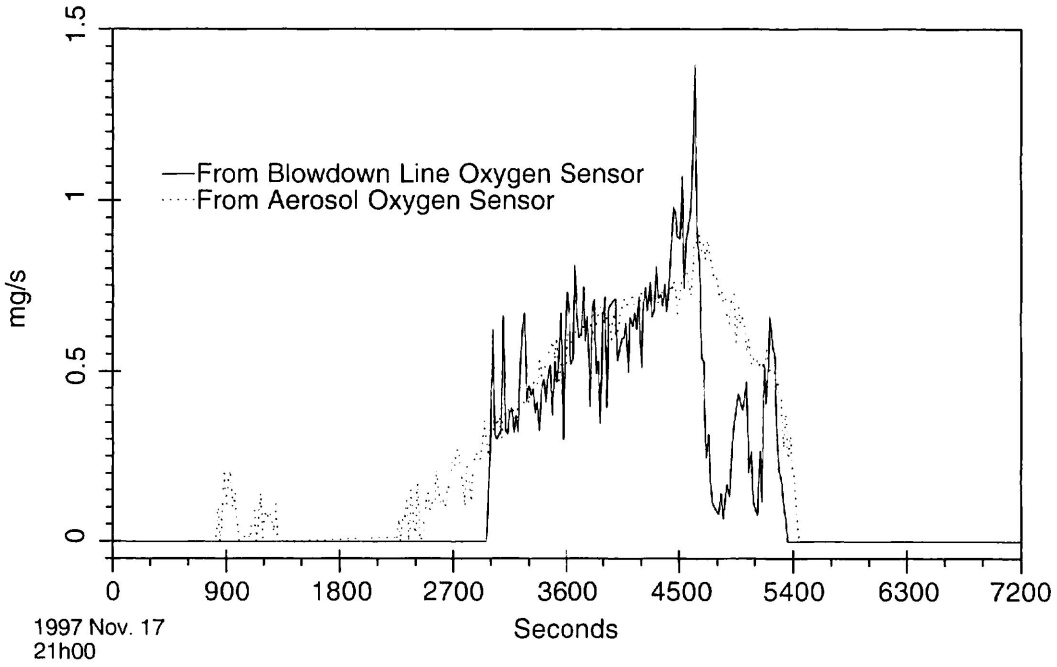

Figure 9: *Hydrogen Production Rates Calculated from Oxygen Sensor Data*

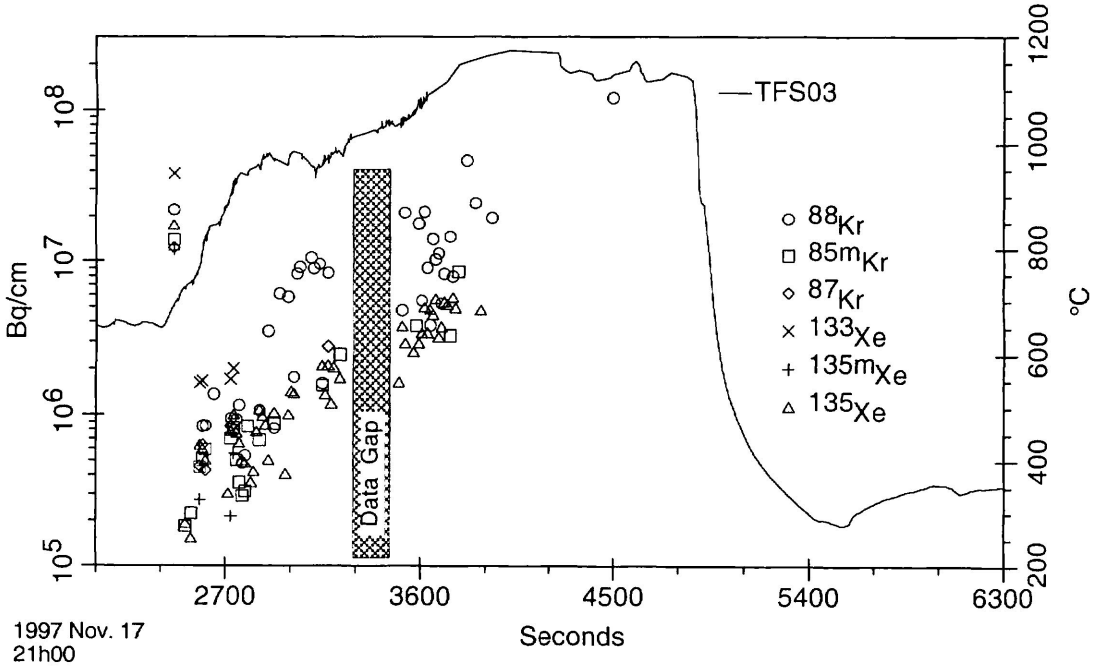

Figure 10: *Noble Gas Activity at NW4 and Sheath Thermocouple Temperature*

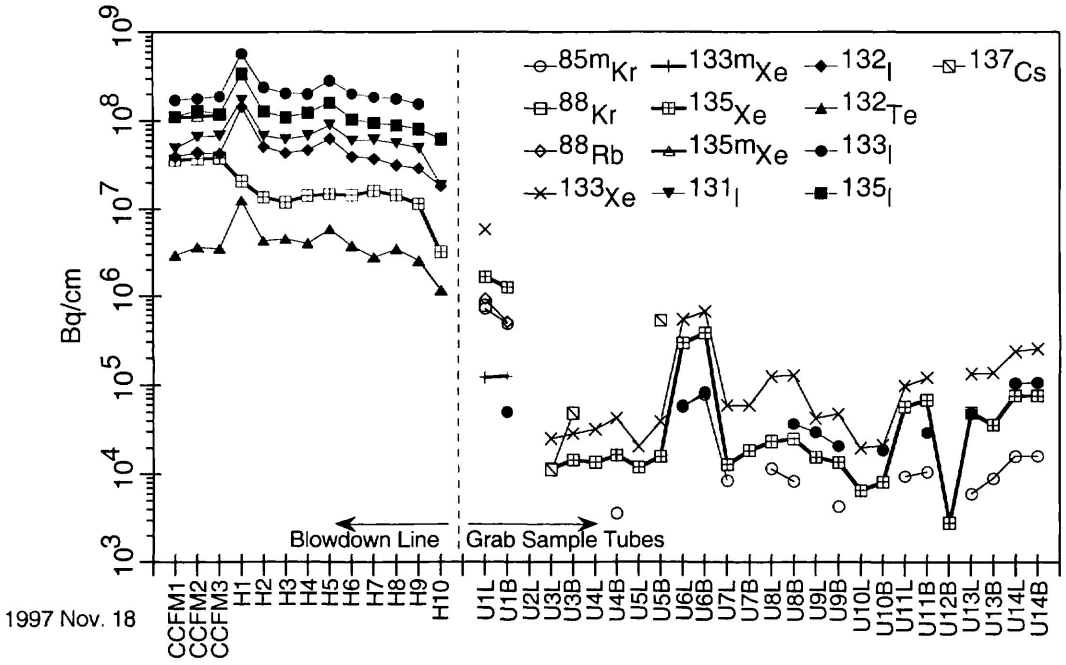

Figure 11: *Header & Grab-Sample Activities, Morning After Transient*

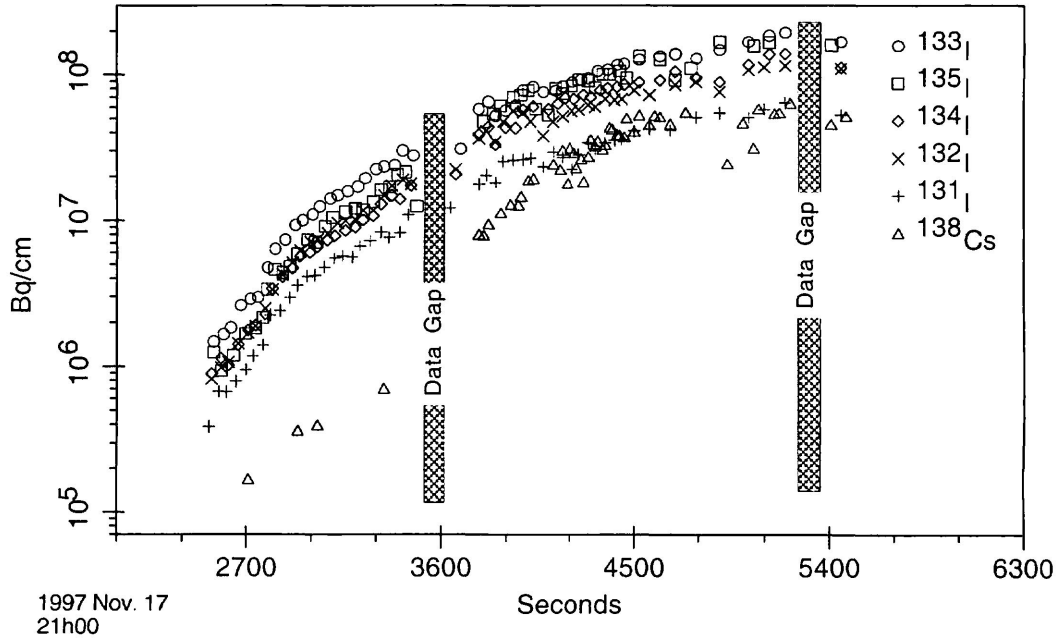

Figure 12: *Iodine and Cesium Activity at NW2*

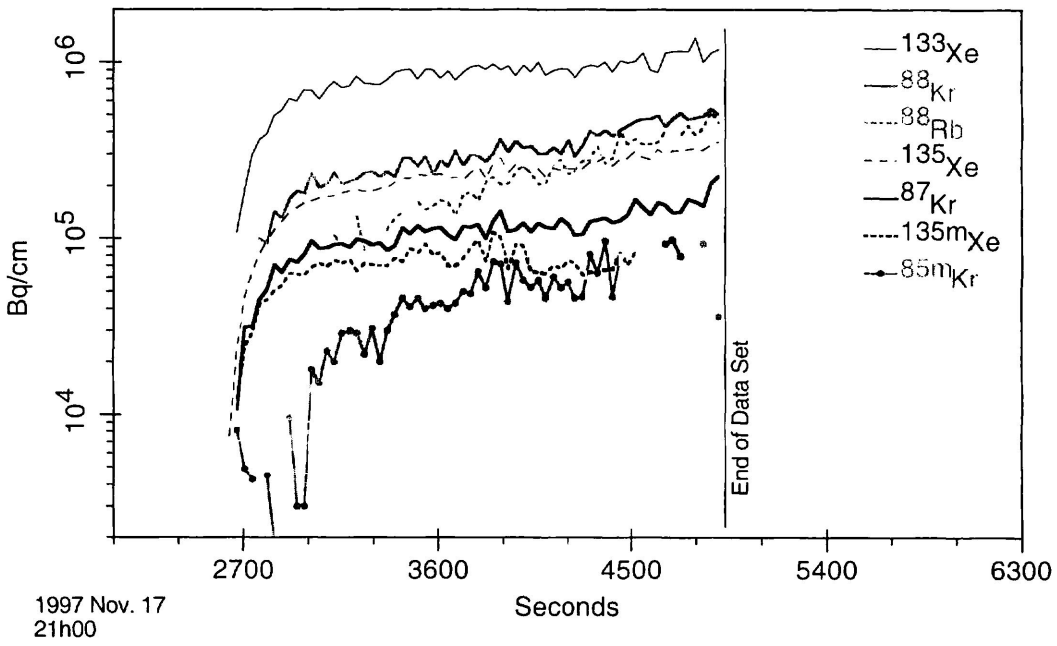

Figure 13: *Noble Gas Activity in Liquid Side-Stream from Blowdown Tank*

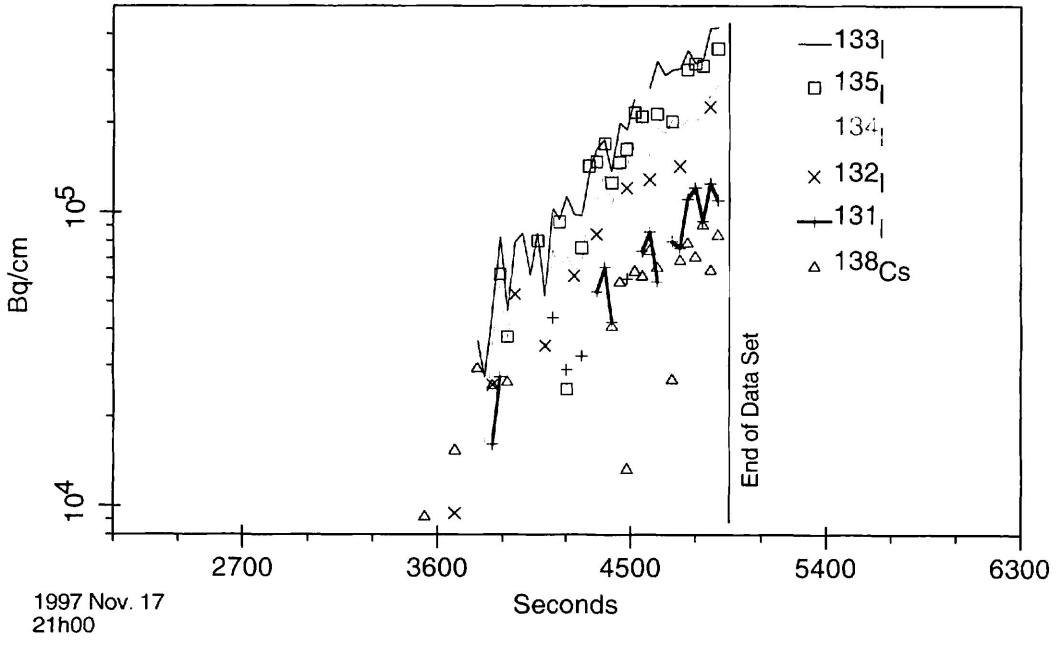

Figure 14: *Iodine and Cesium in Liquid Side-Stream from Blowdown Tank*

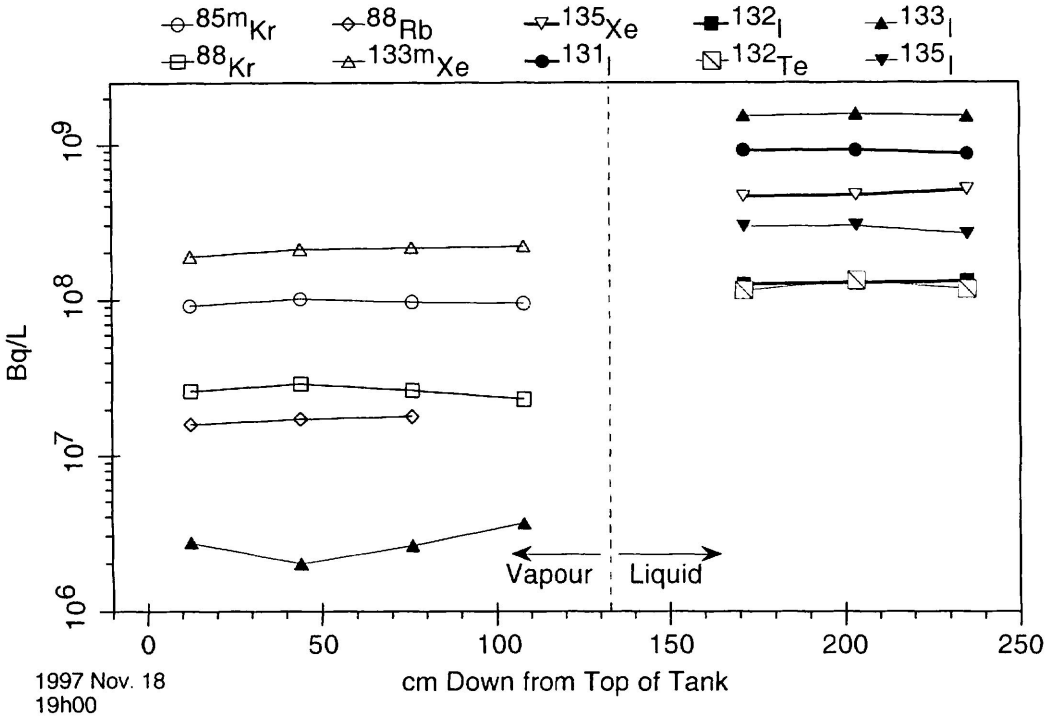

Figure 15: *Blowdown Tank Activities, Day 2*

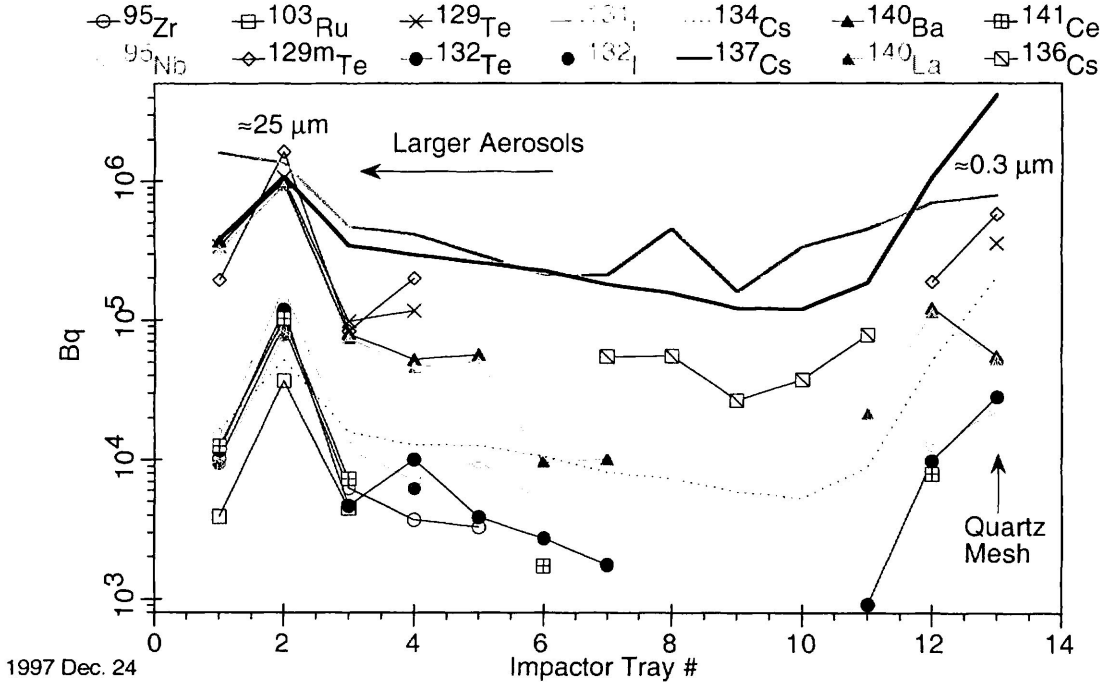

Figure 16: *Activities of 1st Cascade Impactor Tray Liners*

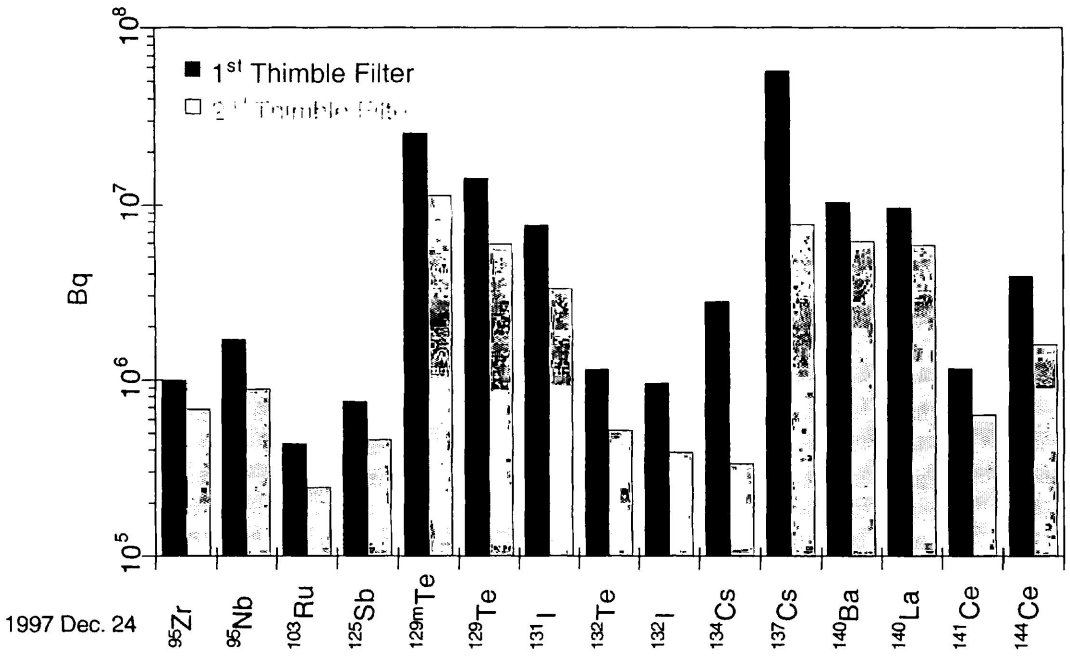

Figure 17: *Thimble Filter Activities*

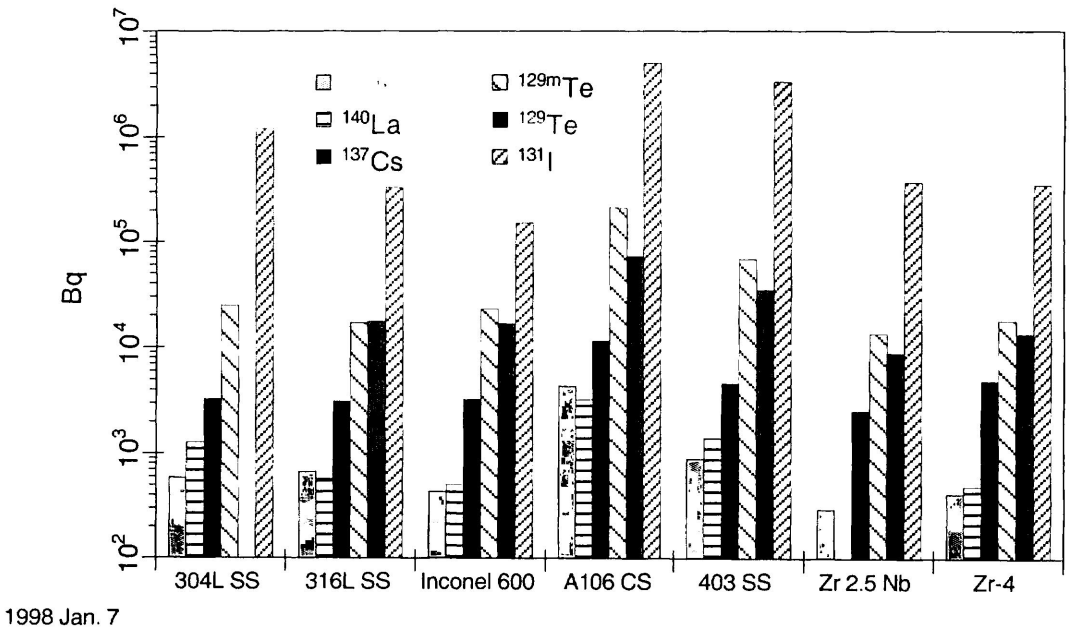

Figure 18: *Activities of Blowdown Tank Coupons*

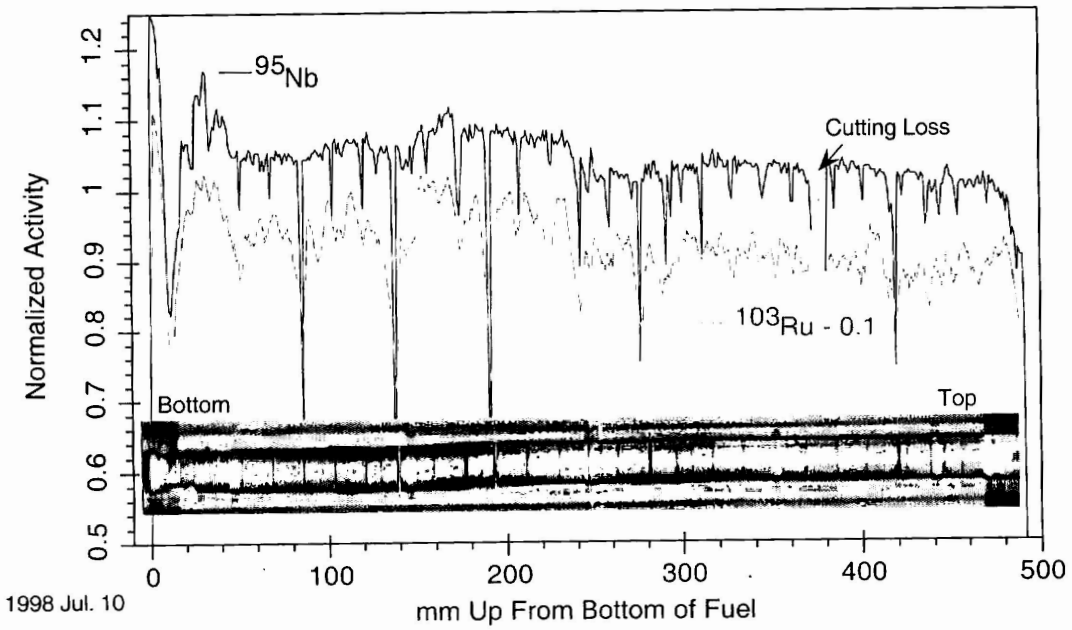

Figure 19: *^{95}Nb, ^{103}Ru Activity Along Fuel Element*

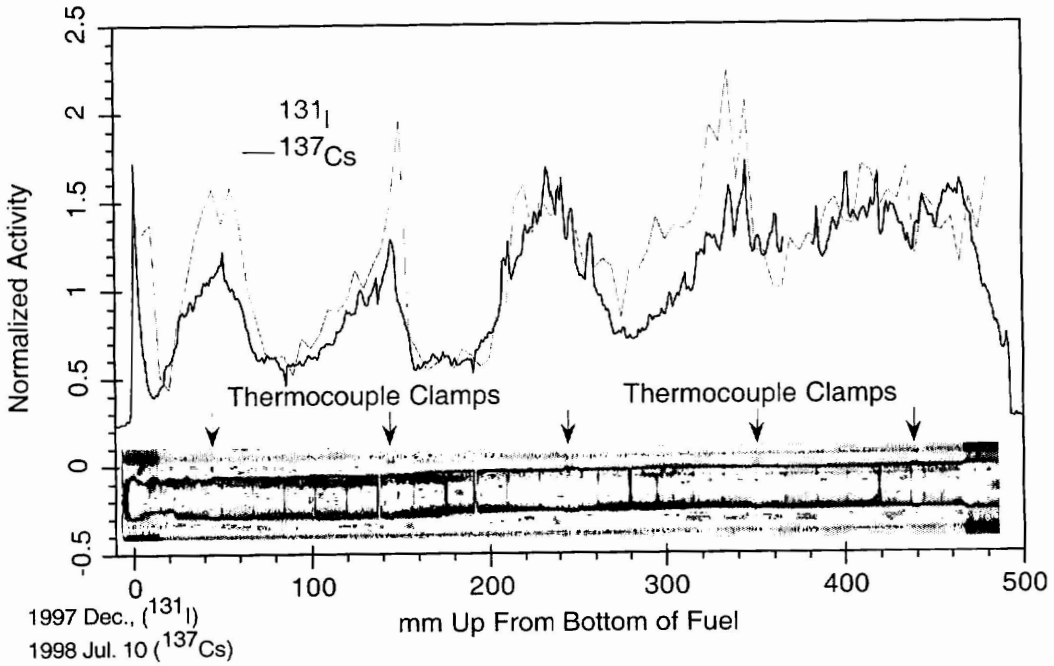

Figure 20: *^{131}I, ^{137}Cs Activity Along Fuel Element*