DARLINGTON NGS
FUEL DAMAGE INVESTIGATION
AN OVERVIEW

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Introduction

On November 30, 1990 with the Unit 2 reactor operating at 100% full power, a routine recycle fuelling operation was attempted on channel N12. The channel closure and shield plugs were removed and an empty fuel carrier was advanced into the inlet end fitting with no difficulty. However, at the outlet end of the channel, a fuel carrier containing two irradiated bundles from channel Y08, which were being recycled into N12, stalled short of its home position.

The fuel carrier was finally positioned with difficulty but the ram could not advance to push the fuel into the channel. Despite the application of high forces, and with the fuelling machine under operator control in semi-automatic mode, the ram could not be advanced. The front face of the fuel in the carrier was left approximately four inches short of the fuel latch. The fuelling operation was aborted and the fuel carrier was retracted from the outlet end fitting. However, problems were encountered while trying to rotate the fuelling machine magazine, which was an indication that fuel could be protruding from the fuel carrier. After several stalls, the magazine was rotated. During insertion, the shield plug stalled short approximately one bundle length. In addition, the closure plug could not be reinstalled. Indications were that there was debris in the outlet end fitting and both the Gaseous Fission Product monitor and heat transport system chemical analysis were indicating damaged fuel in the south loop, the loop containing channel N12. Reactor power was reduced to 65% full power in early December and operated until December 23, 1990 when the unit was shutdown to install a maintenance cap on the end fitting.

Unit 2

Unit 2 fuel load started on June 17, 1989 and First Criticality was achieved on November 4, 1989. Due to problems unrelated to fuel, Full Power was not achieved until July 1, 1990. Unit 2 was operated at high power levels for most of the period from July to November, 1990 until the incident occurred.

Following successful disengagement of the fuelling machine from the reactor face and installation of a maintenance cap on N12 East, on January 4, 1991, the fuelling machine was returned to the Fuelling Facilities Auxiliary Area. On January 12, 1991, the fuel carrier containing the Y08 bundles was discharged to the Irradiated Fuel Bay, at which time fragments of fuel elements from the bundle in position 1 were discovered. Unit 2 was shut down and an investigation into the cause of the fuel damage was initiated.

The evidence from the fuel fragments (subsequently confirmed) was that part of the N12 position 1 bundle, consisting of some centre and inner ring elements broke free of the bundle and moved through the fuel latch prior to the refuelling attempt.

Subsequent to the shutdown of Unit 2, in-reactor inspections of the downstream end plates of selected bundles in position 1 and 13 were performed with CIGAR (Channel Inspection Gauging and Recording) video camera inspection equipment. Inspections were done on three separate occasions in 1991; February 12-17, May 16-21 and May 31-June 3. The channels inspected are shown in Figure 1. The first inspections revealed cracks in D2K12/1 (Darlington Unit 2 Channel K12 bundle 1) and D2Q12/1 downstream end plates. The second inspecton period concentrated on channels away from the centre columns 12 and 13 of the reactor face, except for channels C12 and E12. The inspected endplates showed no visible indications of cracks but channels R06, F07, and H03 were flagged for abnormal marks on the end plates. During the third inspection three channels, J13, H12 and R13, presented indications of cracks and two channels, L11 and E11, were flagged as indicating possible cracks. Subsequent inspection in the Irradiated Fuel Bay on the downstream end plates of the H12 and R13 position 1 bundles, confirmed the presence of a crack in R13 and that H12 was not cracked.

Following the first CIGAR inspection, preparations were made to ship irradiated fuel to AECL's Chalk River Laboratories and Whiteshell Laboratories for examination in hot cells.

The hot cell examinations provided the best quantified characterization of bundle damage, including detailed end plate crack characterization and also bearing pad and spacer pad fretting wear. Observations of visually indicated partial and incipient cracks in the hot cell examinations were influential in directing the early Irradiated Fuel Bay inspections and CIGAR video camera inspections.

Inspection of discharged fuel bundles in the Irradiated Fuel Bay (IFB) is a normal part of fuel performance monitoring. However, following the N12 fuel damage finding, a significantly expanded program of IFB fuel bundle inspections was initiated. The initial focus was to inspect discharged bundles from the first charge of Unit 2 that were available in storage modules in the fuel bay. The available bundles were those from positions 10, 11, 12 and 13 which had been discharged during normal four bundle shift fuelling.

By the end of April 1991, a number of channels with visible end plate cracking indications from CIGAR video camera inspection were defuelled. Inspection provided evidence of extensive fuel string wear and damage in channels D2K12, D2K13 and D2J13, ranging from multiple cracks in a number of bundle positions, through heavy spacer sleeve interaction wear on outboard bearing pads of bundles in position 13, to varying degrees of inter-element spacer pad and end plate impression wear along the fuel strings.

Characterization of damaged fuel in Unit 2 has recently been completed. Endplate cracks have been identified on fuel from 8 channels (J12, J13, K12, K13, M13, N12, Q12 and R13). Severe bundle 13 bearing pad wear, due to interaction bearing pad with the spacer sleeve, has been observed on fuel from 7 channels (J13, J14, K07, K12, K13, M12, V20).

CIGAR pressure tube inspection has been performed on 19 channels. Fuel Channel K13 was replaced due to a 0.5 mm deep fret mark, as well as a desire to physically examine fuel channel components. Recently, the entire assembly was sent to CRL for characterization.

The CIGAR inspections did not identify any other pressure tube that has to be replaced, although channel N12 will be changed due to fuel debris in the end fitting liner.

Unit 1

Unit 1 fuel load started on August 1, 1990 and first criticality was achieved on October 29, 1990. Full Power operation was achieved January 12, 1991 and continued until March 9, 1991 when the unit was shutdown for a planned maintenance outage. AECB approval to restart the unit was not secured until August 10, 1991 due primarily to concerns over the fuel damage found in Unit 2. As part of the Unit 1 restart, an extensive data collection program, similar to that undertaken on Unit 2, was undertaken. The unit operated from early September 1991 to October 17, 1991 when another planned maintenance outage started. Extensive fuel inspection program during this period of operation did not identify any significant fuel damage. AECB approval to restart the unit was obtained December 24, 1991 and the unit operated until January 26, 1992 when heat transport iodine levels exceeded the revised (more restrictive) shutdown limits. The Iodine excursion was later found to be due to debris fretting wear of fuel elements and was not associated with endplate cracking or excessive bearing pad wear. Subsequent to the shutdown, an endplate crack was identified during IFB inspection of a bundle from channel M13. As well, significant bearing wear was observed on fuel discharged from two channels (H13 and K18). It was concluded that the same mechanism which caused the damage on Unit 2 was present on Unit 1, and the decision was made not to restart the unit until a design solution was installed.

Organization

Following the identification of fuel fragments from channel N12, an investigation team was established. The initial technical review team was established as an ad-hoc group of Ontario Hydro, AECL-CANDU and General Electric (Canada) personnel, with representation from operations, project design, functional design, fuel inspection, fuel handling and nuclear safety. By February 15, 1992, a formal investigation team structure and evolved. This team focused upon two objectives:

- determination of the cause of the N12 failure, and
- determination of implications of the N12 event for continued operatoin of Unit 1 and returning Unit 2 to power.

Technical review meetings of the investigation team, held weekly, were initiated in late January 1991. Initially, the investigation team made recommendations to Darlington NGS and, when required, reviewed the priorities of actions proposed by operations to protect Unit 1 and return Unit 2 to power.

Working groups with assigned leaders were established to direct and co-ordinate activities in the following areas:

- Fuel inspection and assessment
- In-reactor inspection
- Station chemistry
- Metallurgy
- Unit 2 rehabilitation

Nuclear Safety and licensing activities were maintained under the already existing responsibilities of the Operational Safety Engineer - Darlington, in the Nuclear Safety Department.

In early March 1991, a Darlington Fuel Damage Investigation and Recovery Program Steering Committee was established. The committee consists of the Vice-President's of the Design and Construction and the Nuclear Operations Branches, and other members of senior management in the two branches. The chairman of the investigation team and the manager of the Nuclear Safety Department are members of this committee. With the establishment of the Steering Committee, the reporting of the investigation team was changed from Darlington NGS to the Steering Committee.

The structure of the investigation team was modified in May, 1991. This modified structure reflected the increased scope of activities related to fuel design and performance, the increased scope of out-reactor loop testing to include a wide range of hydraulic as well as mechanical vibration issues and the rapidly expanding fuel inspection program. In addition, because of planned testing on Unit 2 with restarted pumps, a planning and integration function was established.

A futher modification to the structure of the team occurred in August 1991 following the testing performed on Unit 2 during the period July 6 to July 15, 1991. This change reflected the expanded effort in activities related to interpreting the hydraulic flow and aocusti data acquired during Unit 2 testing and associated hydraulic modelling activities.

A noted above, the investigation team structure and membership has evolved as the scope of activities has changed. The current organization is shown in Figure 2.

Investigation

The initial activities of the investigation team were concentrated on evaluating potential scenarios whereby the observed break-up of the N12 bundle in position 1 could have occurred, assessing the potential implications of bundle break-up occurring in-reactor, establishing a fuel inspection plan and reviewing operating history. The work was focused in large measure on identifying the causes of fuel damage observed in Unit 2 as shown in Figure 3.

The first scenarios addressed involved possible fuel manufacturing defects, excessive force during manual loading of the first charge fuel, debris fretting damage to the end plate, and possible mechanical overload of the bundle by overextension of the fuelling machine ram during the N12 fuelling operation. With very limited information available, the most logical scenarios were ones involving mechanical overload induced ductile failure mechanisms which could damage the position 1 bundle.

In parallel, tests were initiated in the flow visualization rig at the AECL Sheridan Park Engineering Laboratory (SPEL) to investigate the vibration behaviour of loose elements in a downstream bundle and possible vibration induced fretting of the pressure tube. There was a suspicion that low cycle/high amplitude fatigue was the mechanism that had caused the break-up of the D2N12/1 bundle, based on preliminary results of detailed examination of an endplate fragment from D2-N12/1 at Chalk River Laboratories. A series of tests were performed in the SPEL flow visualization rig with pumps cycle on and off. However, these tests did not produce any end plate cracks, which indicated that low cycle/high amplitude fatigue was a doubtful mechanism to cause the observe damage.

On Unit 1, a series of vibroacoustic endfitting vibration and pressure pulsation measurements were taken and these measurements indicated pulsations and vibrations at the 150 Hz vane-passing frequency of the pumps, as well as components at 30 Hz and in the 6-12 Hz range. Since the pressure measurements were taken at the end of long instrument lines, the 6-12 Hz components were most probably associated with instrument line resonances excited by broad-band turbulent eddies in the flow. Conflicting views existed regarding the significance of the higher frequency pressure pulsations and vibrations, resulting in a wide range of varying hypothesis being formulated in the ensuing months. As part of the effort to resolve issues pertaining to possible fuel damage mechanisms, testing on Unit 2 was performed in July 1991, and on

Unit 1 during the August, 1991 restart. Hydraulic, fuel bundle and fuel string modelling and analysis were also initiated in this time period.

During the period from April 1991 to early June 1991, a wide range of analysis and testing activities were focused around possible low cycle fatigue mechanisms: large amplitude flow variations due to pump starting and stopping, flow variations due to boiling at channel exits, static bundle overload due to excessive hydraulic drag load, flashing and waterhammer pressure surges in the ROH balance lines and pressure surges associated with pump startup. These areas were pursued, in part, because of observations from the operating history of Unit 2 and, in part, from the postulation that cracks could have been initiated by some event, or series of events which had stressed end plates severely, leaving the endplates susceptible to crack growth and propagation due to lower amplitude cyclic loads.

Details of many of the programs that have been undertaken to support the investigation team are provided in other papers.

Conclusion

An intensive, wide-ranging investigation in to the causes of the Darlington fuel damage has been underway since the occurrence of the N12 event on Unit 2. Although this investigation has not yet concluded, a number of definitive statements regarding the fuel damage can be made.

Endplate cracking is due to high cycle fatigue occurring at amplitudes just above the fatigue limit. The cracking of Unit 2 fuel bundles appears to have occurred at distinct periods in time and the cracks have developed over a relatively short time periods.

Endplate fretting wear occurs down the fuel string with a high incidence of impression wear occurring at the downstream bundles and at bundle position 9 on Unit 2, while Unit 1 indicates a high incidence at bundle positions 8, 9 and 10. The incidence of wear at bundle positions 12 and 13 is low on both units. This, together with hot cell examination of some wear marks, indicates a predominant relative axial movement along the fuel string. This is also consistent with spacer pad wear, particularly between rings of elements. In addition, the pressure tube fretting wear on channel D2K12 is consistent with the higher impression wear of endplates in the region of the position 8, 9 and 10 bundles.

The spacer sleeve interaction wear of outboard bearing pads shows evidence of axial wear movement, as inferred from fret marks on the bearing pads and the dimensions of the pressure tube fret marks. However, the possibility of channel inlet flow contributing to bundle 13 bearing pad wear remains open. Certainly, the Bruce experience would suggest that some Type 3 wear could be expected, but at a significant lesser frequency than being observed at Darlington. No definitive conclusion has been reached regarding the mechanism, or mechanisms causing bearing pad wear.

The clearly established 150 Hz resonances in the reactor inlet headers and inlet feeders at hot conditions, together with the indications of a significant number of Unit 2 channels with damage exhibiting good acoustic transmission response, has contributed to this being considered the dominant mechanism causing fuel failure. Practical design solutions have been developed to significantly reduce the amplitude of the pressure pulsations and reduce the heat transport system sensitivity to resonant conditions. These are expected to significantly reduce the potential for incurring further fuel damage. In part, demonstration of the effectiveness of some of these modifications will come from Unit 3 testing.

Acknowledgement: The author would like to thank Dr. J.C. Luxat who coordinated the preparation of the "Report on the Investigation to Fuel Damage Causes Following the Unit 2 N12 Event" from which the majority of this paper was taken.

FIGURE 1
UNIT 2 CHANNELS INSPECTED BY CIGAR VIDEO EQUIPMENT

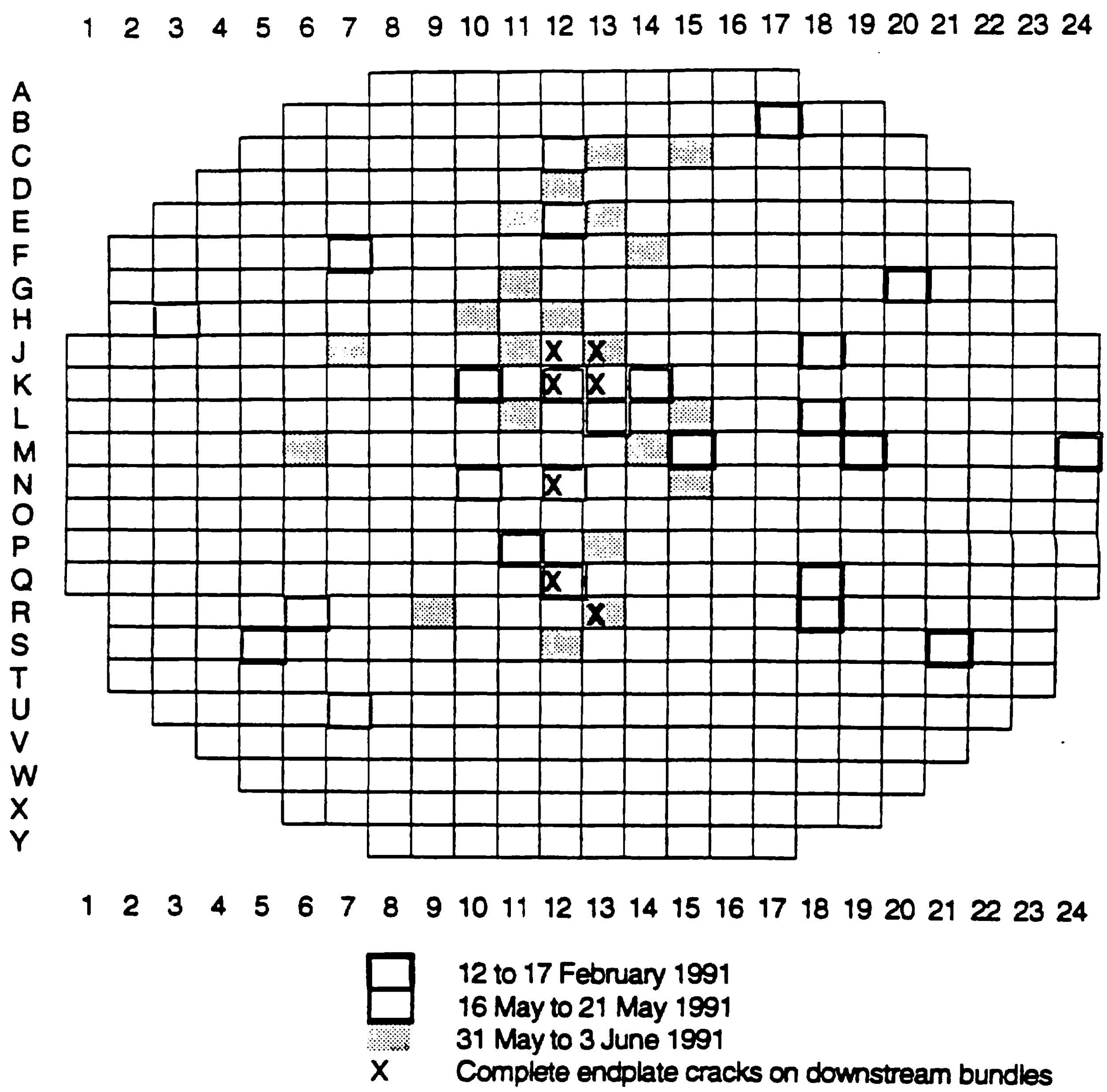


FIGURE 2

Darlington N12 Fuel Damage Investigation Team

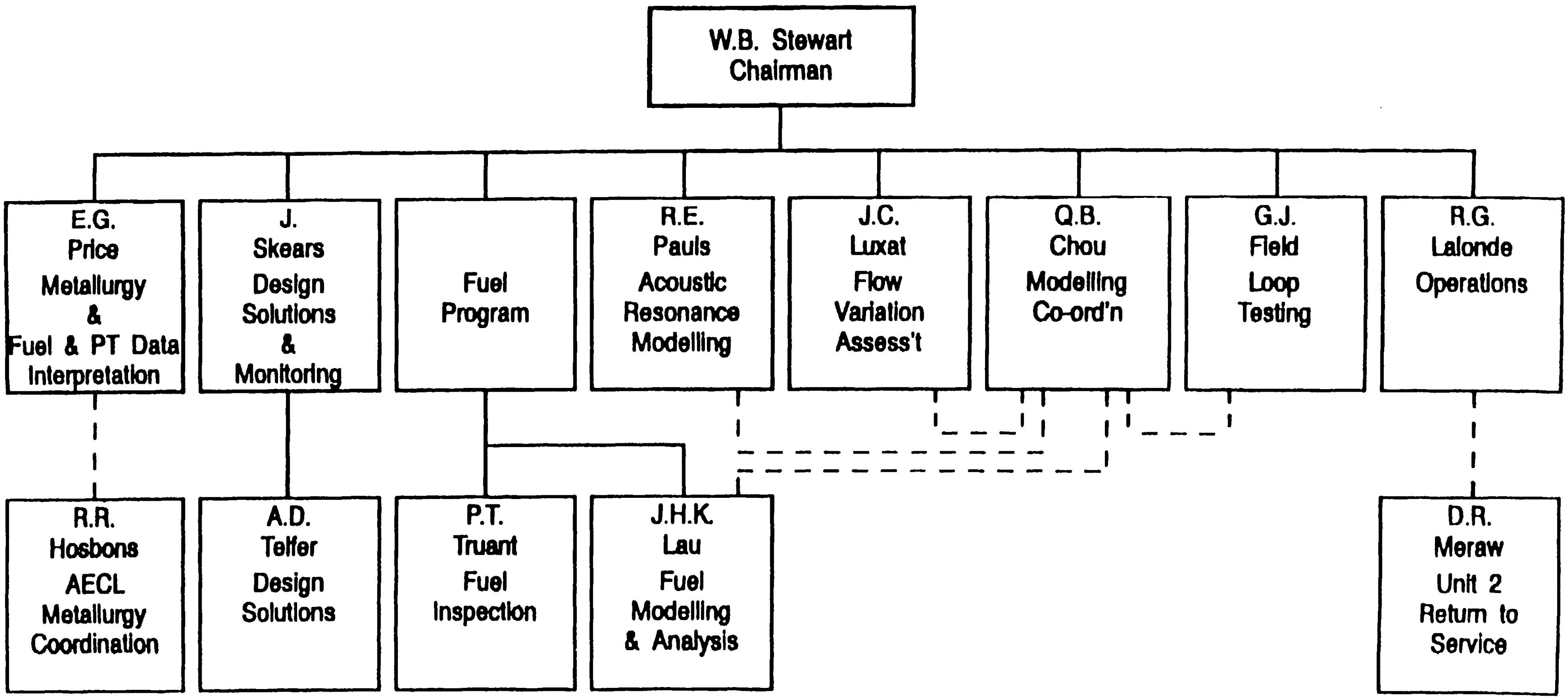
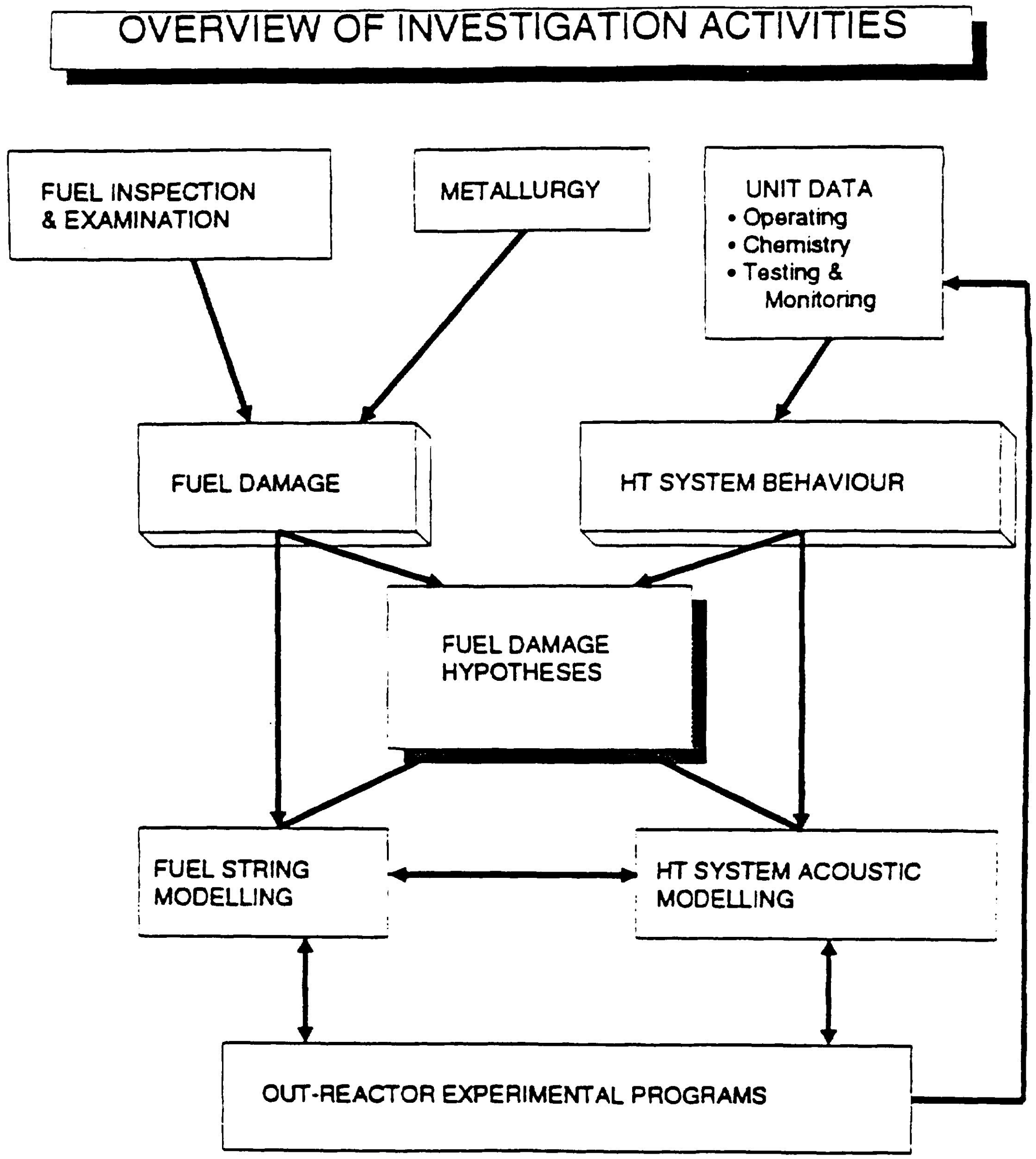


FIGURE 3


OVERVIEW OF INVESTIGATION ACTIVITIES
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