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International Agreement Report

Pre- and Post-test Analysis of LOBI MOD2 Test ST–02 (BT–00) with RELAP5/MOD1 and MOD2 (Loss of Feed Water)

Prepared by
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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

April 1992

Prepared as part of
The Agreement on Research Participation and Technical Exchange
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Summary Sheet

Title

Pre- and Post-test Analysis of LOBI MOD2 Test ST-02 (BT-00) with RELAP5 MOD1 and MOD2. (Loss of Feed Water.)

Author A. H. Scriven
Lab Memo Number TPRD/L/ES 0754/ M 87
Job/Target Number VQ045
Boat Number DA01

The experiment ST-02 (later renamed BT-00) is one of a series of Special Transient tests being perfomed on the electrically heated LOBI facility at Ispra in Italy. This test was designed to simulate a loss of main feedwater transient leading via a steam generator dryout to a long term cooldown using bleed and feed.

The test was prepared by the United Kingdom members of the LOBI Special Transients Task Force, who have the responsibility for final test analysis and reporting. This analysis will be performed with the RETRAN plant transient code.

The RELAP5 MOD2 code has been chosen by the Board for assessment work on the Sizewell Pre-Operation Safety Report. It was originally designed for Loss of Coolant Accidents, but is now finding wider applications. At the request of the code assessment group at GDCD, an analysis of ST-02 using the RELAP5 computer code was undertaken. RELAP5 MOD1 was used for a pre-test calculation, and RELAP5 MOD2 for the detailed post-test analysis. This was to allow cross-code comparisons, assess the possibility of using RELAP5 for pressurized transients and because the final phase of bleed and feed which occurs in test ST02 is more representative of Small Break transients than Pressurized Faults.

This report documents the results of this calculation and comparisons with the test data, but does not bring together the RETRAN calculations or attempt to draw any comparisons between the codes. This latter will be performed as part of an overall code assessment exercise.

After accounting for test conditions and events outside the original specification the RELAP5 MOD2 code was found to perform rather well.

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24/2/88

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24/2/88

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1.0 Introduction.

Experiment ST-02 (BT-00) is one of a series of Special Transient tests being performed on the electrically heated LOBI facility at Ispra in Italy. The rig has been very fully documented for the International Standard Problem 18 (ISP18) and is reported in references 1 through 4.

This test was designed to simulate a loss of main feedwater transient leading via a steam generator dryout to a long term cooldown using bleed and feed. This divides the test into three phases:

1. Loss of main feedwater and boildown of steam generator secondary side to 1m above the tube plate.
2. Dryout of the steam generator secondary side with interrupted auxiliary feedwater flow until primary circuit fluid temperature reaches 325 C.
3. Long term cooldown via primary system bleed and feed.

The test was proposed by the United Kingdom members of the Special Transients Task Force who intend to use the RETRAN computer code to analyse the experiment. Their RETRAN analysis report should constitute the final post-test analysis report which is required to discharge the responsibilities of the test originator. (Chappell and Hirst 87)

The RELAP5 MOD2 code has been chosen by the Board for assessment work on the Sizewell Pre-Operation Safety Report. It was originally designed for Loss of Coolant Accidents, but is now finding much wider applications. At the request of the code assessment group at GDCD, an analysis of ST-02 using the RELAP5 computer code was undertaken. This was to allow cross-code comparisons, assess the possibility of using RELAP5 for pressurized transients and because the final phase of bleed and feed is more representative of Small Break transients than Pressurized Faults.

The work reported here is therefore in addition to the RETRAN final analysis report, and does not attempt to cover the test in great detail. Exact specifications for the test can be found in the Experimental Data Report issued by the LOBI team (Sanders and Ohlmer 1986), which also reports the test results in every detail.

The test was performed at the end of 1985.

2.0 Calculations performed.

2.1 *Pre-test RELAP5 MOD1 calculations.*

Previous calculations of LOBI tests had been performed with the RELAP5 MOD1 code used on the IBM/VM system at CERL. At the time of the ST-02 test the latest code version was the RELAP5 MOD2 code which was only usable on the CRAY computer at Harwell

At the request of GDCD this test was to be performed with the MOD2 code, but because of extensive experience with the local code version, together with the extremely convenient interactive code setup and execution, it was decided to to make a pre-test calculation with the local RELAP5 MOD1 code to show an ability to model the main test features and to allow initial debugging of the input deck to be performed quickly and cheaply.

Therefore prior to the test being performed, an input deck for the ST02 test was set up based on an existing LOBI input deck as used for ISP18, BL00 and BL02 calculations reported previously. Changes were made to model the boundary condition specified for the test, and to include the test specific options.

Two runs were made. The first run showed that the sizing of the small relief valves on the secondary side appeared to be insufficient to allow the desired control of secondary side pressure. These sizes had been inserted into the input deck as best estimates at a time when exact valve data was not available.

Contact with the LOBI team suggested that the areas in the Relap input deck should be increased to allow correct control.

This was done using manufacturer's data for valve discharge rates but making no assumptions about the maximum operating speed of the valves. Furthermore, control of these valves was based on simple error correction with rather small time constants, a system designed to fulfil the needs of the test specification, but not based on the actual electronic controllers used on LOBI. The second run with larger valve areas was successful. Only the first 500 seconds of the test were calculated, because the test specifications allowed several operator actions which were to be initiated at the discretion of the operations team, and it was felt that until the test was run calculation of these parts would be impossible. The second calculation agreed exactly with the pretest calculation performed by the LOBI team for ST02, and which was given in the test specification report as the desired response. The Figure 1 on page 3 shows The primary pressure from this prediction.

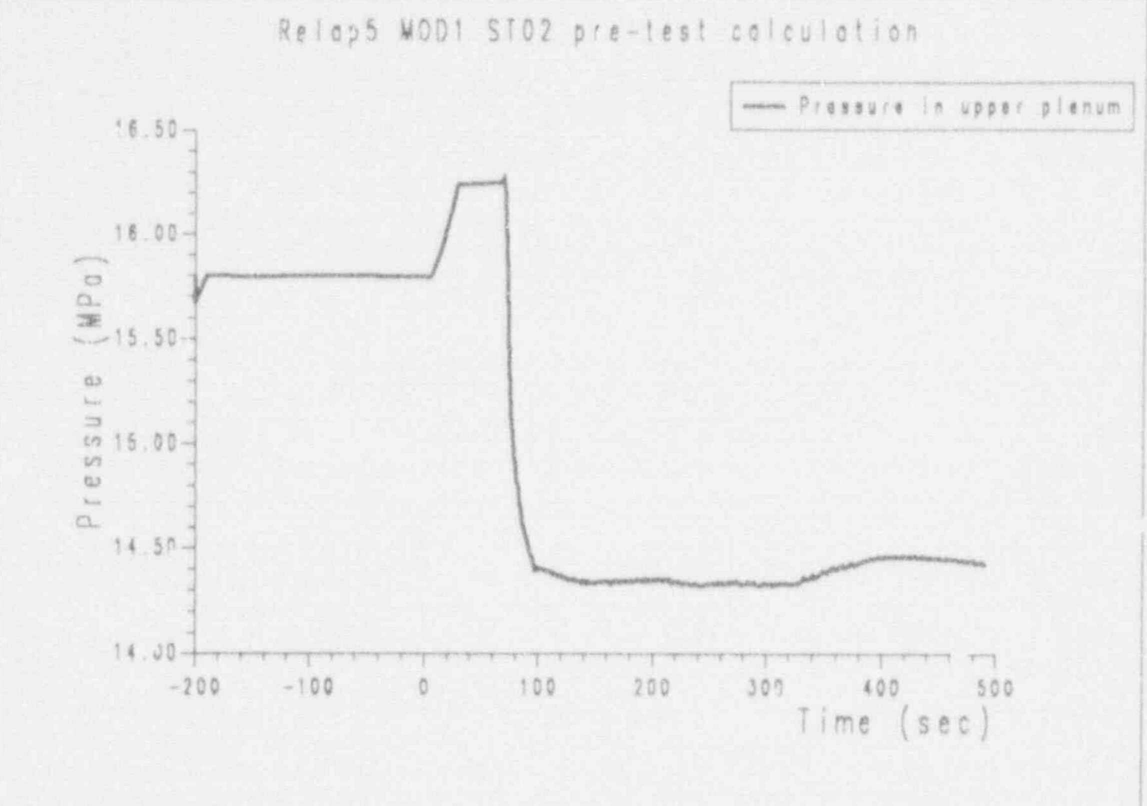

Figure 1. **Pre-test calculation:** Primary pressure response.

As this calculation was seen only as an aid to performing the later MOD2 calculation, no further details are given here.

2.2 Post-test RELAP5 MOD2 calculations.

2.2.1 Conversion from MOD1 to MOD2.

The input deck was then converted to be compatible with RELAP5 MOD2, and a route was set up to allow runs to be performed on the Harwell Cray system. The MOD1 to MOD2 conversion was performed simply to allow the code to run at this stage, not to incorporate the extra features available in the MOD2 code. The code version used was cycle 36.04 with some minor CRAY errors corrected.

Immediately the CRAY system was used the rate of progress dropped off rapidly due to the rather tenuous links to Harwell, the job turnaround times, the slow transfer of data from Harwell back to CERL and the time taken to overcome various problems concerned with remote execution. These were not of course RELAP5 specific problems, but they significantly affected working practice.

During input checking three errors were found in the CRAY version of MOD2 which initially had to be bypassed by changing the input data. Corrections for these were implemented later by W. Bryce, and the latest EG & G version also now incorporates these updates. The converted deck then ran quite well and gave very similar results to the MOD1 calculation.

Some time was then spent in altering the input deck to make use of the extra features in MOD2 such as cross flow junctions, in an attempt to overcome some of the known limitations in vious LOBI calculations. Special efforts were made to incorporate some means of odelling the complex 3D effects seen in the top of the downcomer where bypassed steam and injected HPIS water come together. A trial configuration which incorporated a split upper downcomer and 3 separate bypass paths was tried. Although this achieved the main objectives it caused very slow running and subsequent code failures. This noding had to be abandoned, and the final scheme used is shown in simplified form in Figure 2 which is included below.

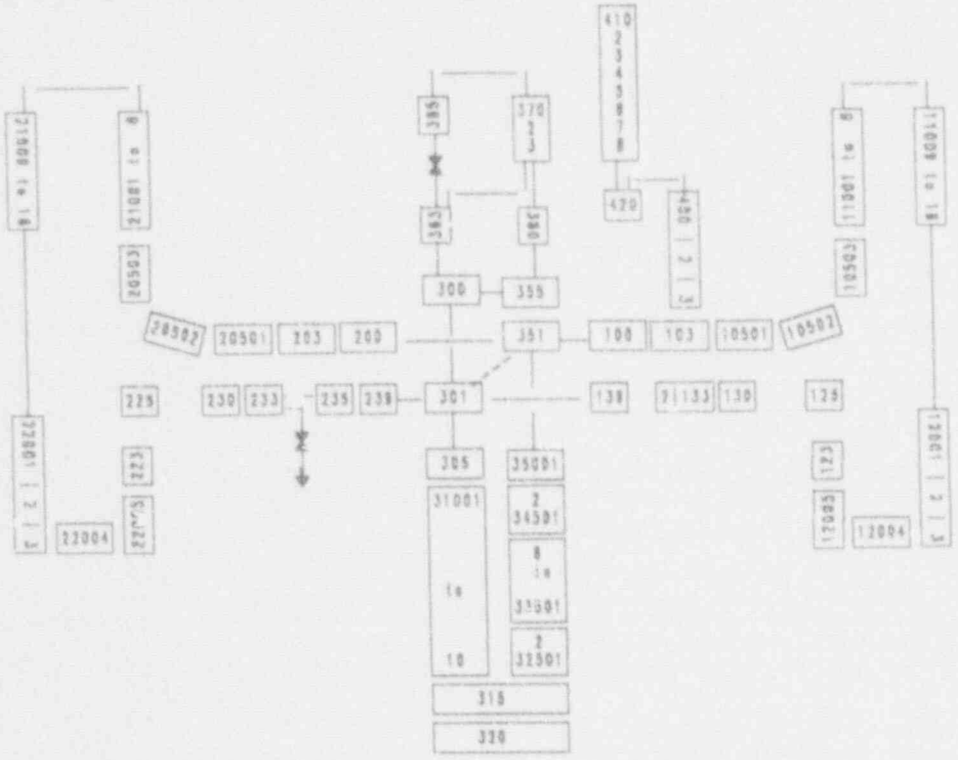

Figure 2. **Noding scheme:** Simplified schematic of primary side.

At the same time improved values for bypass flows resulting from the ISP18 exercise were incorporated. With these changes the deck was ready, awaiting the test results and measured initial and boundary conditions from Ispra. As mentioned previously a pre-test calculation was not deemed a sensible objective due to possible experimental variations.

2.2.2 An overview of the ST02 transient as performed by LOBI.

Following the receipt of the ST02 datatape, work resumed to extract the relevant boundary conditions. Due to a number of effects and occurrences, the test proved to be very significantly different from both the formal specification and the pre-test calculations. These differences were so great as to render any comparisons with the prior predictions meaningless.

A brief summary of some of the main events in the test is given as Table 1 on page 5 and shows the large number of unspecified actions performed in this test. The RELAP5 calculated times on this table are from the final calculation, discussed later.

Description of Events	Timings (s)		
	Specification	Experiment	RELAP5
Loss of Feedwater	0	0	0
Secondary Pressure Control Valve Opens	-	3	3
Primary Pressure Control Valve Opens	-	Unknown	3.5
Pressurizer Safety Valve Opened	-	18	11
Pressurizer Safety Valve Closed	-	19	14
Pressurizer Safety Valve Opened	-	26	16
Pressurizer Safety Valve Closed	-	27	18
Pressurizer Safety Valve Opened	-	-	21
Pressurizer Safety Valve Closed	-	-	2
Pressurizer Safety Valve Opened	-	-	28
Pressurizer Safety Valve Closed	-	-	29
Primary Pressure Control Valve Closes	-	Unknown	36
Operator Opened Secondary Safety Valve	-	42	Input
Operator Closed Secondary Safety Valve	-	49	Input
Operator Opened Secondary Safety Valve	-	58	Input
Operator Closed Secondary Safety Valve	-	63	Input
Power Trip	70	70	70
Start of Auxiliary Feedwater	130	130	130
Secondary Pressure control Valve closes	-	124	138
Secondary Pressure control Valve opens	-	310	200
Finish of Auxiliary Feedwater in Broken loop	Switched on water level of 1m	248	Input
Finish of Auxiliary Feedwater in intact loop	Switched on water level of 1m	1805	Input
Primary Pressure starts to rise	-	2300	1920
Pressurizer heaters switched on	-	4538	3200
Pressurizer PORV opens	-	5900	3800
Start of Bleed and Feed phase	-	5962	3860
Primary and Secondary Pressures cross	-	11000	-
End of test	-	15000	-

Table 1. **Timings of Major Events in the Transient.:** Comparison between test specification, execution and RELAP calculation

A great deal of time was spent in attempting to unravel the course of the transient, and the actions that had been taken by the LOBI team. In order to aid comprehension and clarity, the details of these divergences will be left till later, and what follows is an overview of the main phenomena seen in the experiment as it was performed.

Once the flavour of the transient has been understood the details of the code predictions can be more easily followed.

Consider first the whole transient, shown in Figure 3 on page 6below. Here the primary and secondary pressures are plotted over the entire 15000 seconds, with an insert detail showing the first 150 seconds.

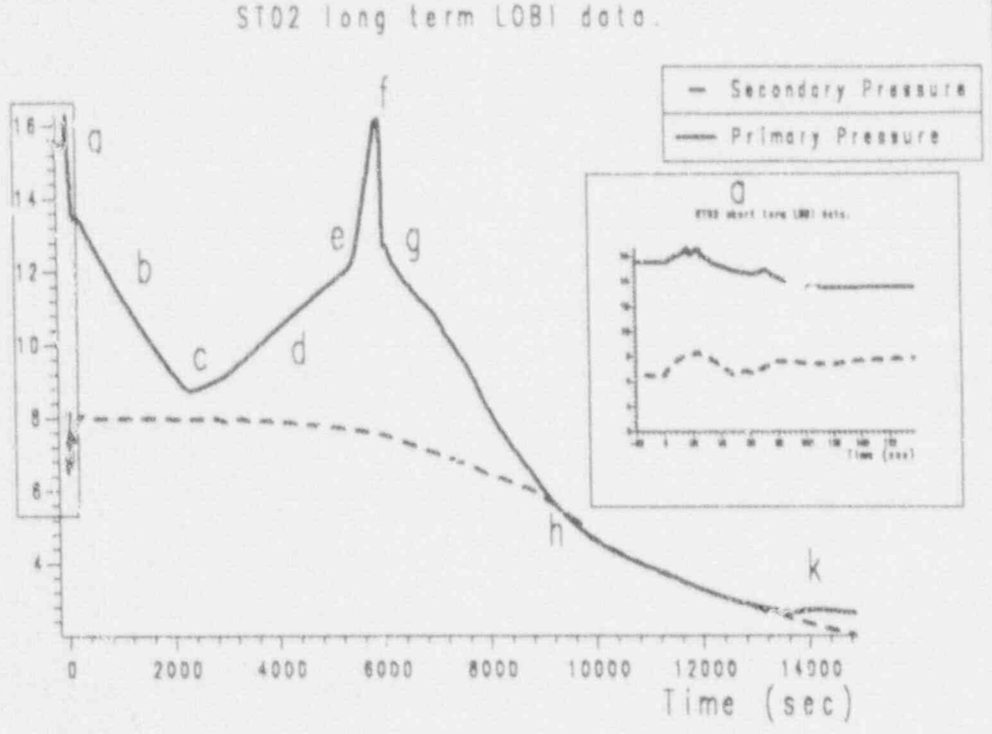

Figure 3. **Overview of whole transient:** Primary and secondary pressures.

The figure has been labeled at various parts with letters from 'a' to 'k'. The part from 'a' to 'c' corresponds to phase one of the original specification, a loss of main feedwater followed by scram, 'c' to 'f' is phase two, in which the auxiliary feedwater is interupted causing secondary side dryout, and 'f' to 'k' is phase three, the bleed and feed cooling.

At 'a' the system response is dominated by system setpoints and the characteristics of the control systems and valves. The exact details of the pressurizer relief valve and steam generator relief valve openings define the observed responses.

At 'b' the system is wholely controlled by the slow loss of heat from the pressurizer. During this time the primary system is subcooled. Only in the pressurizer is there a two phase interface and this maintains and defines the system pressure. As the pressurizer loses heat to the environment, it cools, and the saturation pressure falls. The slope of the pressure decay at time period 'b' thus serves to define the pressurizer heat loss- a previously ill defined parameter for LOBI.

When the level in the intact steam generator reached 1 m above the tube plate, the auxiliary feed was terminated. From this time the systems ability to dissipate the decay heat is removed. The secondary sides of both steam generators boil dry and as the primary temperature slowly rises, and the system pressure continues to fall, there comes a point at which the primary subcooling is lost. The temperature in the hot legs then exceeds that in the pressurizer. Boiling in the main system then defines the system pressure, which starts to rise from point 'c'. The pressurizer continues losing heat and becomes progressively subcooled, filling with water and finally becoming water-solid between 'c' and 'd'.

The slope of the pressure rise at 'd' is determined by the core heat input balanced by the sum of the system heat losses. In the original pre-test calculations this was expected to be much more rapid, the main errors being in the assessment of the heat losses from the steam generators. To speed up this phase on the test and move into the third phase, the LOBI operators turned on the pressurizer heaters, around point 'd'. This began to reduce the pressurizer subcooling, and finally at point 'e' the pressurizer went two-phase, re-establishing a vapour bubble, and hence lowering the liquid level.

The result was a faster system repressurization up to the point at 'f' where phase three was initiated by opening the PORV on the pressurizer. However the primary pressure was now controlled by the temperature in the pressurizer, the main loops again becoming subcooled, although with steadily rising temperature.

When the PORV was opened at 'f', there was rapid discharge of vapour, causing the pressure to fall, between 'f' and 'g'. As soon as the pressure fell to the saturation pressure defined by the main loop temperatures, the pressure fall slows as boiling round the system begins at point 'g'. Extrapolation of the pressure rise from period 'd' through 'e' to 'g' shows that the primary loop temperature continued increasing with the slope seen during period 'd', despite the pressurizer heaters being switched on. Thus the pressure spike imposed between 'e' and 'g' can be thought of as superimposed on the rather slow transient caused by the gradual loop heatup.

The Figure 4 below clarifies this point.

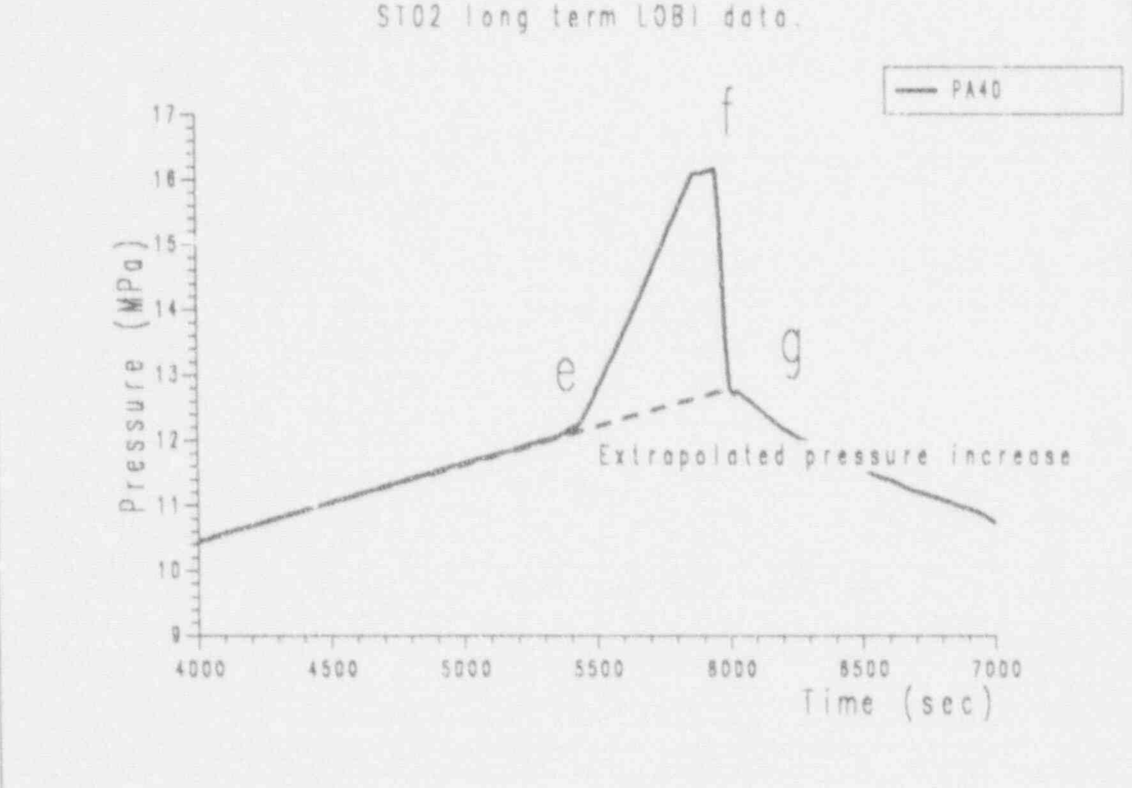

Figure 4. Effect of pressurizer heaters operating: Expanded pressure plot.

There is a small increase in the rate of pressure fall just after 'g' when the High Pressure Injection comes on, but the system continues to depressurize, boiling off fluid and emptying the loops.

The steam generator U-tubes drain, thus degrading the heat transfer between primary and secondary systems. This reduces the energy transferred to the secondary side, and between 'g' and 'h' the secondary side pressure falls more rapidly.

At 'h' the primary and secondary pressures coincide, the heat transfer reverses, and the rate of primary pressure fall slows, giving rise to the 'knee' in the pressure curve.

Refill of the primary system by the HPIS eventually balances the discharge from the PORV and by 'k' the primary pressure stabilizes while the secondary pressure continues to fall.

During the test the core remained covered, and there was no heatup of the simulated fuel rods. In the extension of the fuel rods above the core, necessary to deliver electrical power, there was a slight temperature excursion following opening of the PORV, when the system fluid drains from the upper plenum.

The overall agreement achieved with the post-test RELAP5 MOD2 calculation is shown in Figure 5 below.

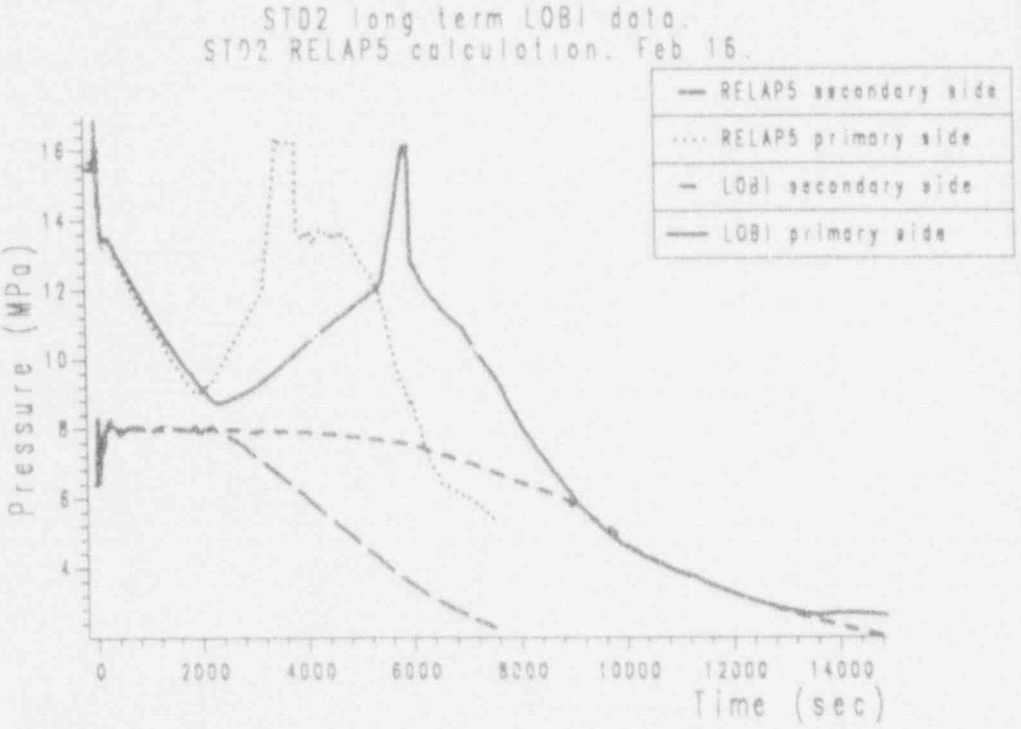

Figure 5. Global comparison: Post-test calculation.

This calculation, performed on February 16th 1987 roughly 1 year after the experimental results had been received, represents the final calculation, a number of partial computations having been made previously. Differences remaining between the test and calculation can be understood in terms of LOBI specific effects, and are not due to modelling problems, so further refinement, although quite feasible, was considered unnecessary. The following sections describe the work leading up to this final prediction, and discuss detailed comparisons for various stages of the transient.

2.2.3 The early transient.

This part of the transient, shown as 'a' on the overview, took the most work. This was partly because of the timescale of events, partly due to the number of poorly defined actions, and mostly due to the perceived need to produce a good fit to this section because of the long-term effect on the rest of the transient.

2.2.3.1 *Initial conditions.*

It is normal to have to adjust the initial conditions in a calculation to match the actual boundary conditions of the experiment. Based on the values found on the datatape this was done for the pressures, temperatures and flows. Furthermore it appeared that the main steam valve had been closed at time zero, rather than the specified 1.5 seconds, and this was altered too.

More problematic was the state of the secondary side. On the broken loop side, an instrument failure had resulted in the liquid level not being measured correctly. This caused the controller to malfunction, and the broken loop steam generator began the test with a level far too low. The exact value is not known due to the instrument failure. Using the differential pressures provided on the datatape which *were* valid, the liquid levels in the steam generators were plotted over time in Figure 6 below.

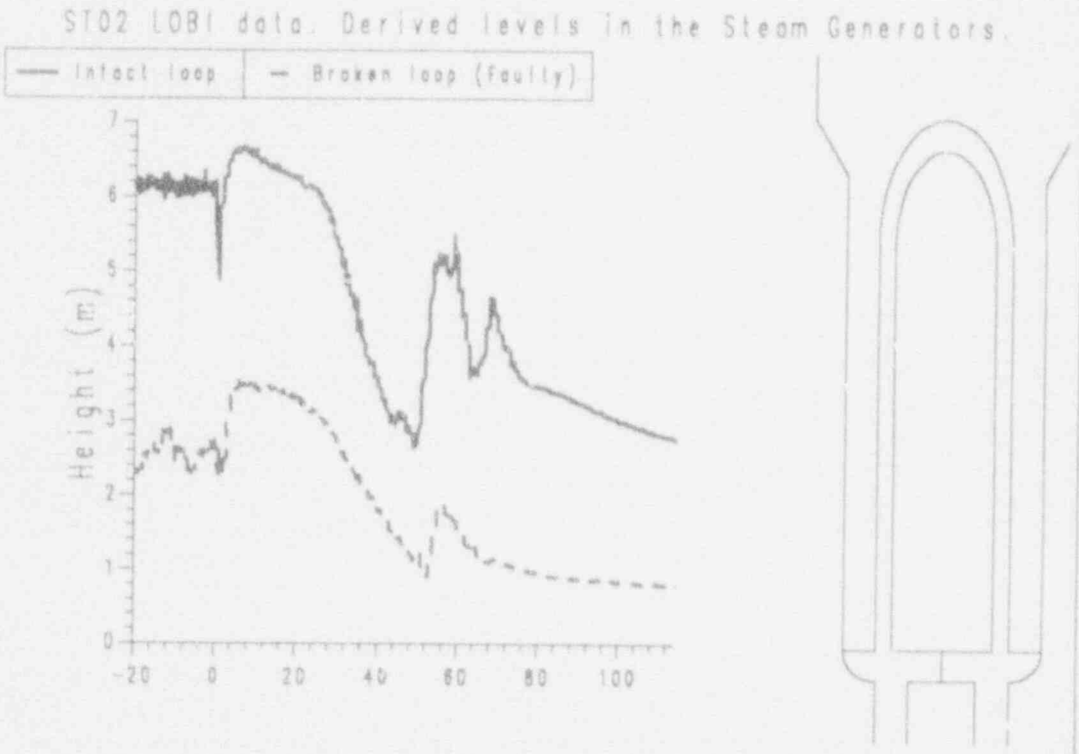

Figure 6. Calculated liquid levels: Secondary sides.

These level are valid after they settle out at around 100 seconds. By comparing the ratio of the intact to broken loop at this time, and assuming this same ratio existed prior to the initiation, a workable value for the initial level in the broken loop steam generator was derived. However, this value is quite critical in determining the time taken to boil down the steam-generators and controls the heat transfer to some extent, so by applying this approach an unavoidable uncertainty has been introduced into the calculation.

Because some events had been defined on steam generator levels this instrument failure also causes dramatic changes in the timing of certain events, as will be seen later.

To assess the accuracy of this initial value guess the RELAP calculated and the LOBI derived levels were plotted together.

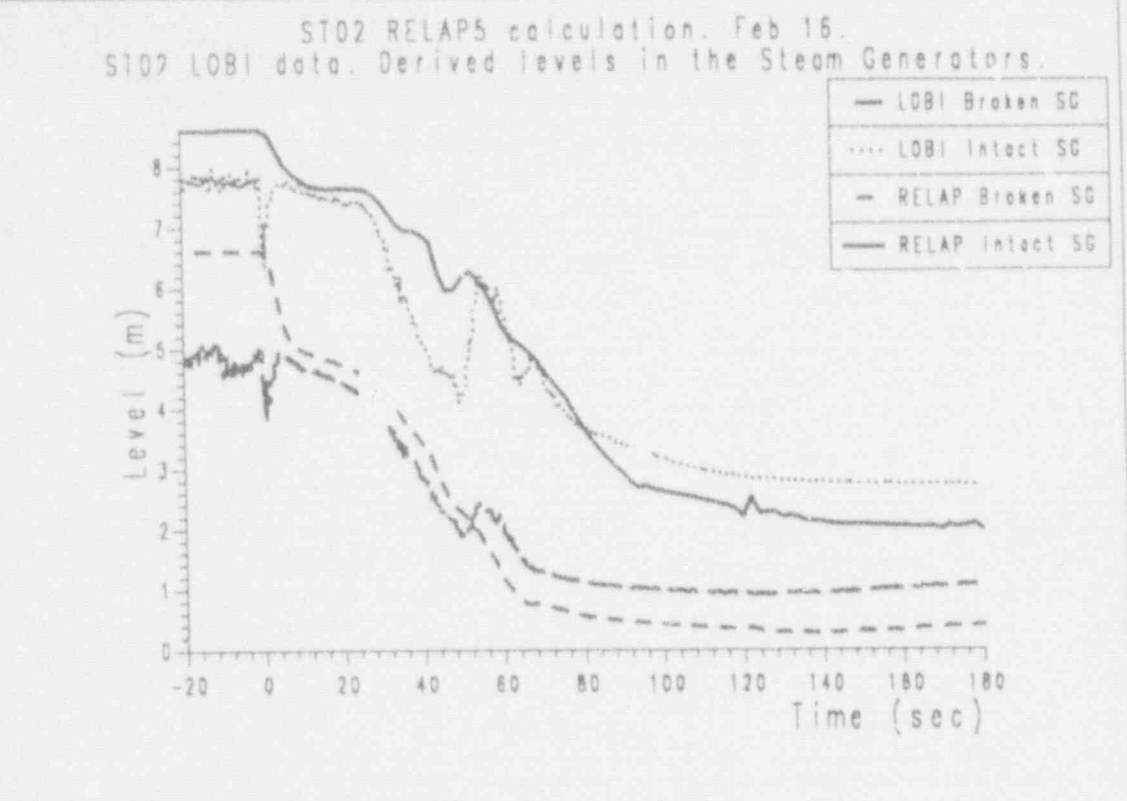

Figure 7. **Secondary side levels:** RELAP and LOBI

Remembering that on the broken loop side the LOBI derived level is not usable at time zero, the subsequent fit is seen it be reasonable, with the exception of the final levels on both intact loop and broken loop sides. This is due to the excessive boiloff of liquid through the relief valves in the RELAP calculation. Although quite a small error, this was found later to influence some timings as the steam generators boiled dry.

The auxiliary feed was specified to come on in both loops 60 seconds after scram, which had been fixed at 70 seconds so from 130 seconds water is being added to the secondary side.

2.2.3.2 Unexpected events.

The original specification for this test defined complex control of both the primary and secondary pressures by means of a control valve and a relief valve on the pressurizer, and relief valves on the steam generators. This was incorporated in the pre-test calculation. In the event the systems implemented by LOBI to perform this control were found to be inadequate for the task. The results for the primary and secondary side pressures can be seen in Figure 8 on page 11 and Figure 9 on page 12

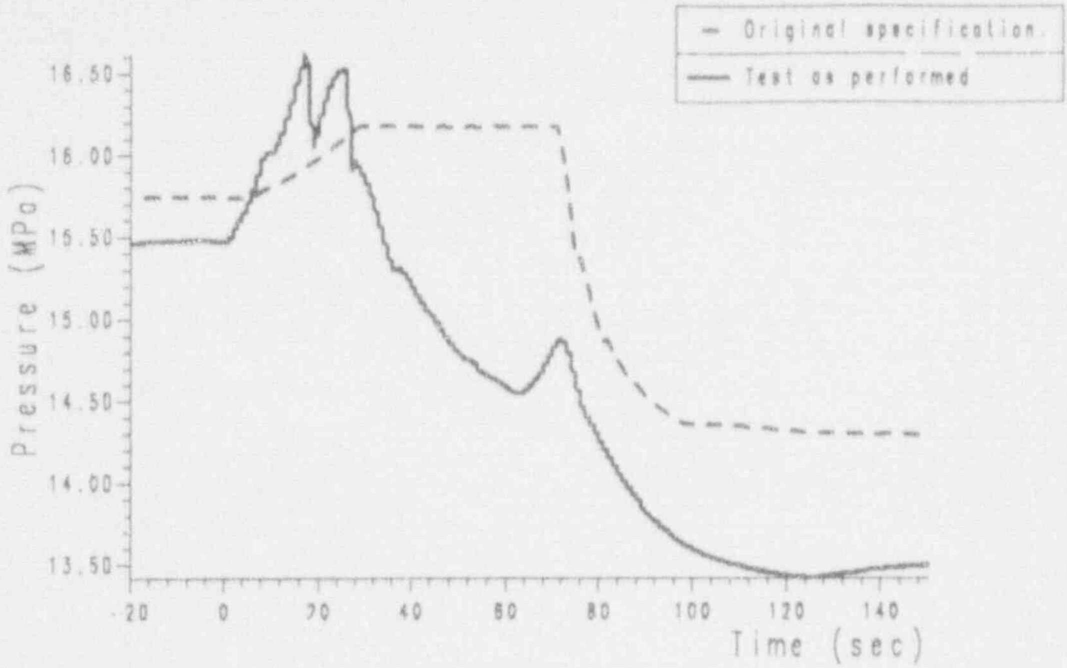

Figure 8. Pressure responses: Primary side.

The major factors were the rates at which the valves were opened and closed, not the final full open valve areas. Correspondence with LOBI following the test revealed that:

- All the valves have mechanical limits on their open/close time, and these range from 1 to 50 seconds.
- Each valve is proportionally actuated by an electronic controller which has individually settable characteristics.
- The exact setting of these controllers was not recorded for this test.
- As a result of the slow opening of the control valves, overpressure occurred on both the primary and secondary sides, resulting in unspecified opening of backup valves, the exact timings and actions again being ill-defined.

For the primary side, seen above, the control valve opened far too slowly following the initial pressure increase. Far from limiting at 162 bar as specified, the pressure rose rapidly to over 165 bar and caused the quick opening relief valve to open automatically. The very large flow through the equivalent area of 3 UK PORVS resulted in a sharp fall, whereupon the valve closed and the cycle repeated, giving the two pressure spikes seen around 20 seconds.

The valve opening times can be deduced from the pressure responses, but the masses discharged are uncertain as the measured fluid velocity appears significantly affected by the response of the turbine flow meter to the short bursts of flow.

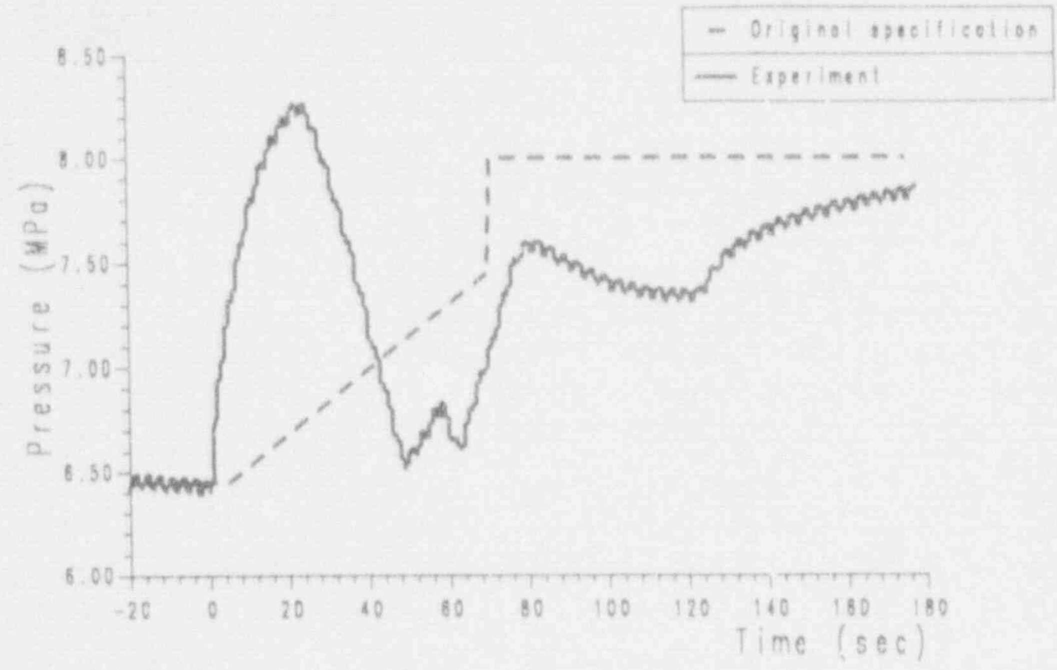

Figure 9. Pressure responses: Secondary side.

On the secondary side things were somewhat worse. Again as can be seen the system failed to control to the desired pressure curve, which was based on turbine run down. This time, seeing the pressure rising rapidly, an operator intervened manually to open extra pressure relief valves in the steam line. These events were not recorded and can only be inferred from measurements in the steam line. It appears the valves were opened manually twice at around 42 and 58 seconds.

In this case the timings are not clear from the pressure response and some explanation of the resulting oscillations is required. Remember that the control valve had an area sufficient to discharge the necessary mass, but that the opening of this valve was sluggish. As the valve slowly opened from 0 seconds, the pressure rose very sharply. The controller, using an integrated error signal for control, demanded a fully open valve. By about 20 seconds the valve was sufficiently open to cause the pressure rise to turn round, but then continued to open as the error signal was still large. Correspondingly after the pressure falls below the desired value at 40 seconds, there is an undershoot in the controlled pressure. Thus the initial peaked pressure response is just due to the time constant for the combined valve/controller being too large when compared to the rates of pressure change experienced. The system was under-damped.

The issue is complicated by the manual operator actions. Opening the backup valve at 42 seconds simply makes the undershoot worse. When this is closed, around 50 seconds, the pressure begins to climb back towards the desired control curve, but is prevented from reaching it by the second manual operation of the valve at 58 seconds. Again the pressure is dragged down, and when this action is terminated, the pressure is some 5 bar below the specified value.

Subsequent oscillations slowly converge on the specified 80 bar control pressure.

2.2.3.3 Modelling the early transient.

The above behaviour is very hard to model. Had the valves been operated correctly, then sufficient mass would have been discharged to produce the desired pressure curve. Under these conditions the valve flow characteristics do not matter, and this was the philosophy behind the pre-test modelling.

Because the valves open too slowly, the critical flow through them at the various openings sets the pressure response via the rate of steam blow-off. It is then necessary to know the exact flow through the valves as a function of of valve opening, and the opening characteristics themselves.

To better model the discharge of the valves a small RELAP5 input deck was set up and calculations made to predict both unchoked and choked flow through the valves at various openings. Comparing these results with the manufacturers rated flows, it was found to be impossible to match both the choked and unchoked data with a single valve area.

It was therefore assumed that the manufacturers data for unchoked conditions was most accurate, and the valve areas which gave the best RELAP5 calculated flow for these conditions were used. This generally made a difference of about 15% greater area used in RELAP5 for the valve area than was suggested by the manufacturer.

Since the LOBI electronic controllers operate on the valve stem position, a function relating stem position to valve area is needed. The manufacturers data for this is illustrated below.

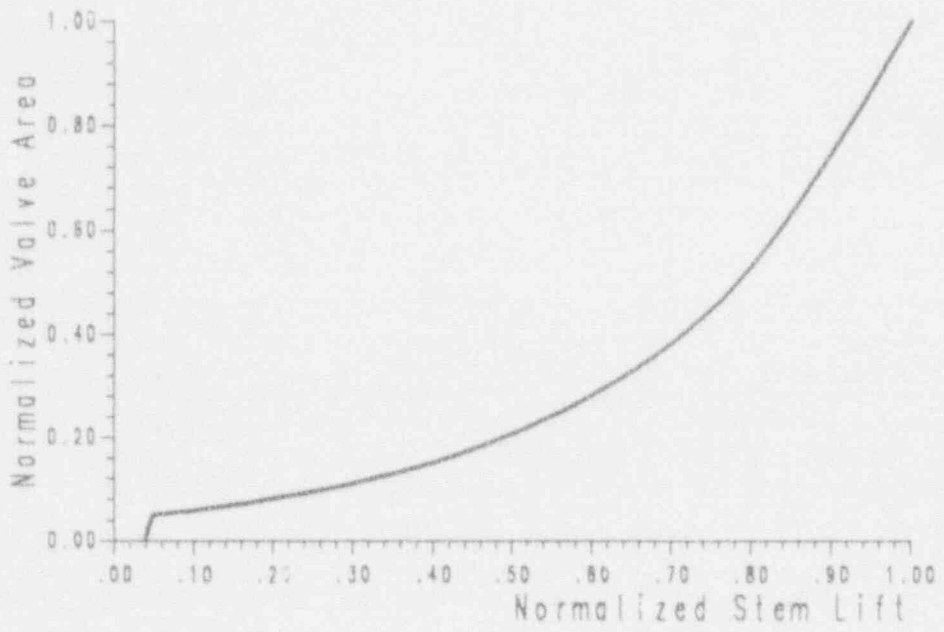

Figure 10. **Valve area versus stem lift:** Manufacturers data.

Unfortunately this is a nominal response. The actual values for an individual valve can be very different, up to 10 percent area difference at each point. Also, critically for this test, the point at which the valve begins to open, nominally at 0.05 stem position, is uncertain. Slight changes in the early part of the opening make large changes in the integrated behaviour, as the initial pressure rise is much reduced and the integrated error signal is then quite different.

Some valves are downstream of orifices of much smaller area than the valve, and therefore have apparently rapid opening and slow closing. This is especially important to model, as the controllers still operate on the full stem travel.

The list of uncertainties for the valve behaviour therefore consists of:

1. Valve discharge rates.
2. Valve areas for given stem position.
3. Settings and responses of electronic valve controllers.
4. Timings and discharges of backup valves.

Several calculations were performed to try various combinations of the above parameters, varying them within the given uncertainties. This was an unusual way to run RELAP, trying to determine boundary conditions from the observed transient behaviour and was expensive in both effort and computer time. Finally results were achieved which were considered to be acceptable. Further 'tuning' could have been performed but was Not considered to be worthwhile. The discharges through the valves, especially on the secondary sides, remove a substantial amount of fluid. Since subsequent events depend on those inventories it is important to begin the test with good estimates, but the pre-existing uncertainty in the initial level in the broken loop steam generator sets a limit on the accuracy achievable.

The results of the final calculation on a short time scale and given in Figure 11 and Figure 12 on page 15.

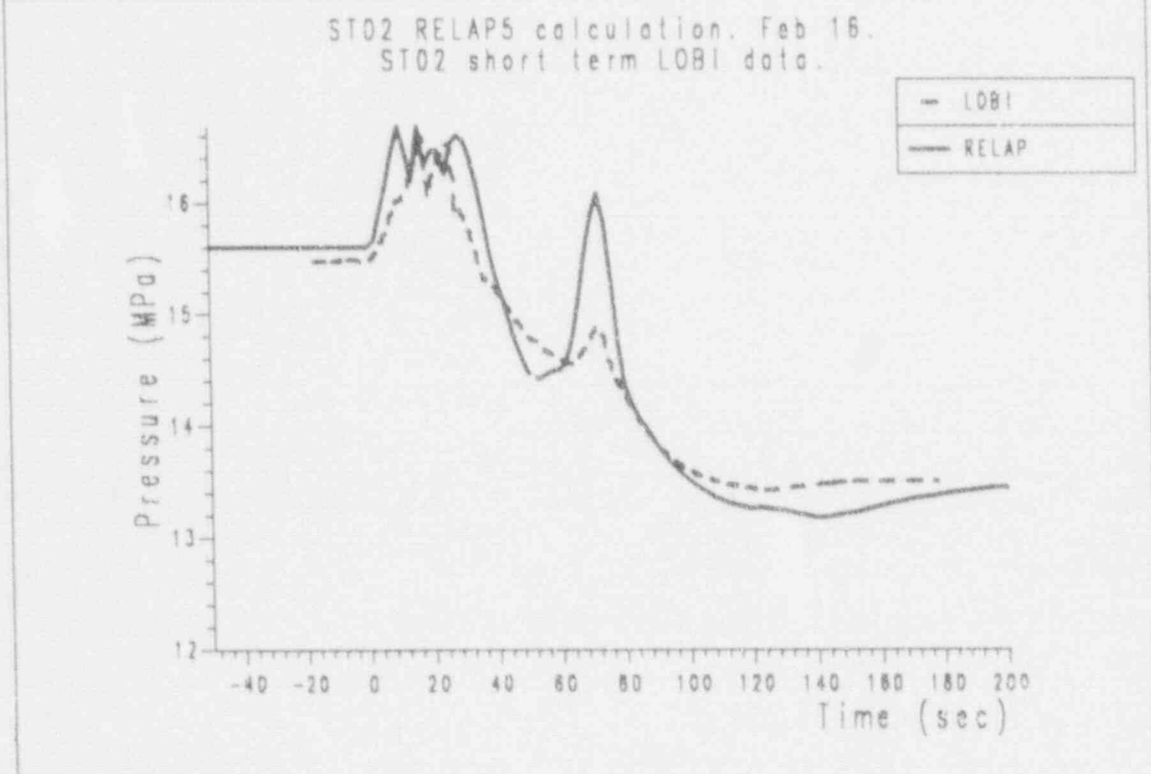

Figure 11. Short term primary pressure. Comparison with data.

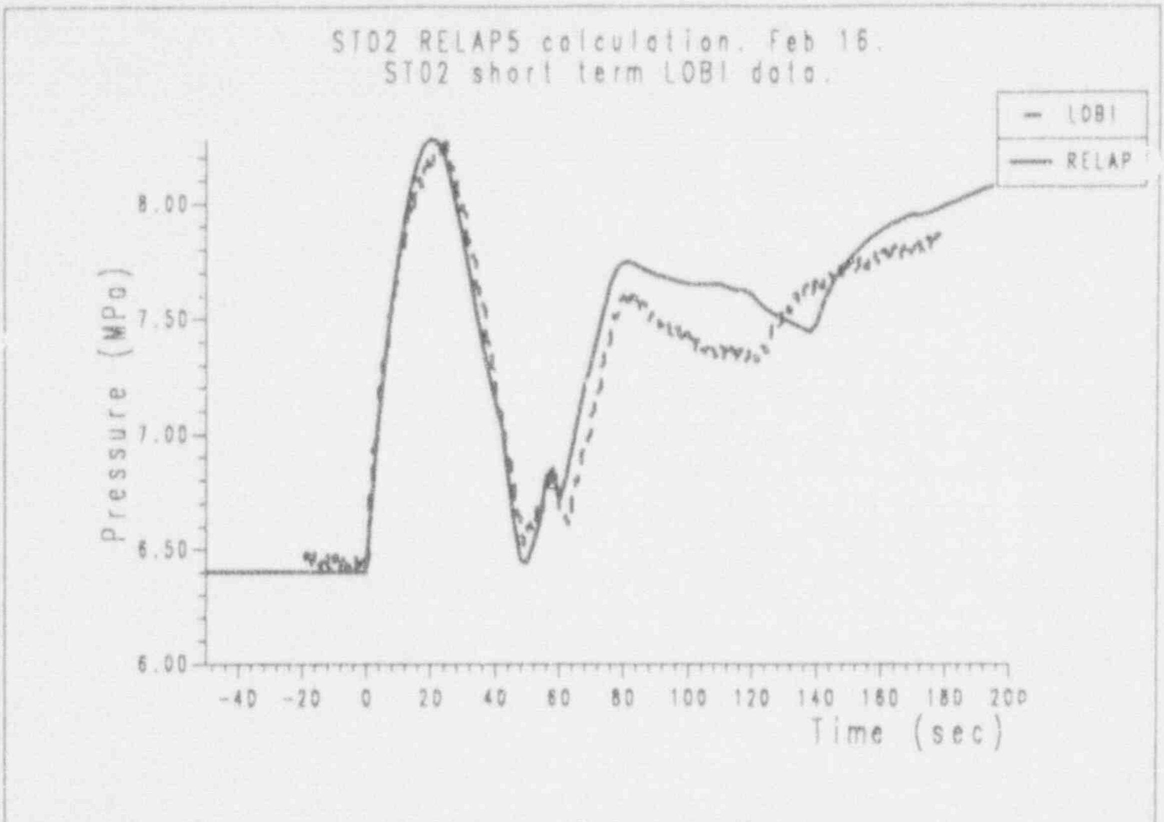

Figure 12. **Short term secondary pressure.:** Comparison with data.

2.2.3.4 Discussion of events.

2.2.3.4.1 Discrepancies between calculation and experiment. On the primary side the two most obvious differences between the calculation and experiment are the four openings of the relief valve on the wider plateau between 10 and 40 seconds, and the greater magnitude of the second pressure spike in the RELAP calculation at 70 seconds. Physically, what is happening is as follows.

At time zero the main feed is lost, and the main steam valve is closed. Continued heat input from the primary raises the secondary temperature and hence pressure. The primary temperature, being controlled by the secondary heat sink, rises also. Thermal expansion of the fluid in the system forces flow along the surge line into the pressurizer, compressing the vapour and raising the pressure. On the primary side this rise is modified by the action first of the control valve on the pressurizer, then by the relief valve, both of which act to 'flatten' the top of the pressure peak.

With the steam generator relief valve open and the secondary fluid boiling off, the temperatures fall, thermal contraction causes an outflow from the pressurizer and subsequent pressure reduction. Plotting both primary and secondary pressures together for the RELAP calculation illustrates these points quite well (see Figure 13 on page 16).

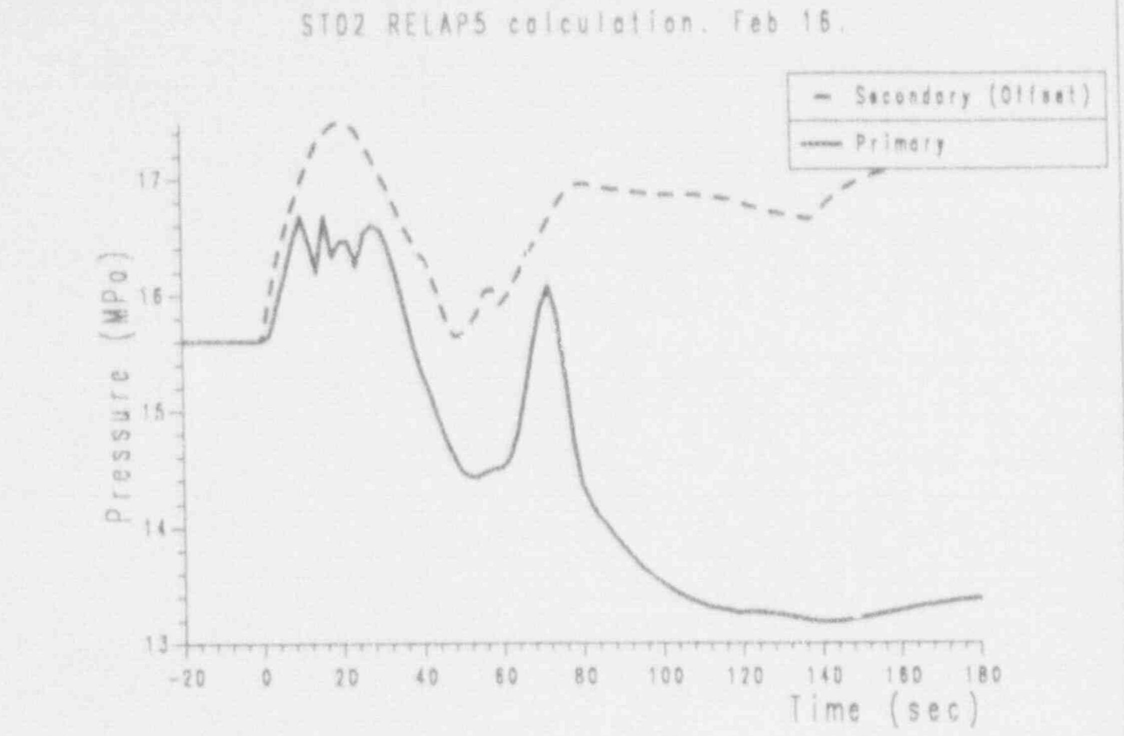

Figure 13. Initial pressure peak: RELAP calculation.

As the secondary pressure rises again around 60 seconds, the primary starts to follow, but at 70 seconds power is scrammed and the primary temperature begins to drop, falling towards the secondary temperature. The two pressure peaks on the primary side therefore seem dependent on the secondary side response.

For the peak at 70 seconds, the overprediction by RELAP is due entirely to the overprediction of the secondary pressure at this time - a consequence of the relief valve responses.

For the initial peak, the cause of the discrepancy is different. Here the secondary side response is very well modelled by RELAP and therefore the primary pressure rise should be correct. In fact RELAP shows a much more rapid rise in pressure than was seen in LOBI. There are a number of effects which *could* affect the pressure.

1. The heatup of the primary fluid, and hence the expansion could be incorrect.
2. The insurge to the pressurizer may be limited by the surge line.
3. Condensation in the pressurizer may reduce the pressure rise.
4. The pressurizer control valve may have opened sooner than was expected, thus mitigating the pressure rise.

Examination of the loop temperatures, and checking of the expansion coefficients ruled out (1).

(2) would only change the pressurizer pressure, the loop pressure would still increase. This does not happen.

(3) was investigated in some detail. A separate deck was set up, modelling just the pressurizer. The surge line flow predicted by the main calculation was used as the boundary condition. Then sensitivities were run looking at the effect of increasing noding detail, increasing heat slab detail and increasing the condensation of steam on the walls. Only increased condensation had a significant effect, which at least showed a well converged

calculation! Even to approximate the LOBI results, however, required a condensation far larger than could possibly be real.

This leaves (4) as the only remaining explanation. To justify this somewhat the LOBI results corresponding to the previously plotted RELAP results are shown below.

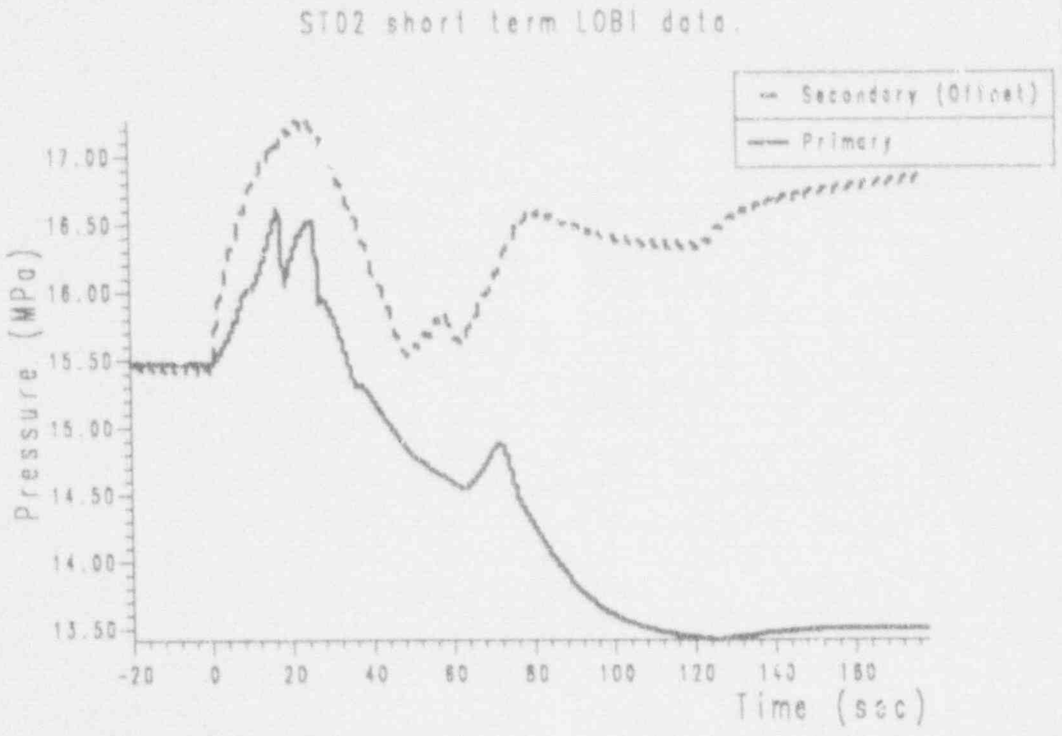

Figure 14. Initial pressure peak: LOBI data.

It is immediately seen that the primary pressure ***does not*** follow the secondary heatup, even very early on. The slope seen does not correspond to the primary side temperature rise, which matches the RELAP calculation quite well. It has to be assumed that the control valve on the pressurizer, which was specified to control on a rather strange condition of

$$162 \text{ bar} - 5\frac{dp}{dt}$$

opened almost immediately the pressure began to rise. This is possible taking into account the uncertainty in the initial stem position at which the area becomes non-zero. This means that the entire shape of this pressure peak is defined by control valve behaviour, not physical phenomena. Deciding this, it appeared that the early transient on both primary and secondary had been calculated well enough to proceed with the main, and most important phase of the calculation, and further effort on minimizing the existing discrepancies would be ill considered.

With the above effects noted, the agreement between calculation and experiment is very good; especially in the small details which reflect the underlying physical phenomena. Two of these will be highlighted below.

2.2.3.4.2 Degradation of heat transfer to the secondary side. The faulty initial level in the broken loop steam generator produces an interesting result. As water is boiled off from the secondary side with the relief valves open, the inventory falls. Initially, the rapid vapour generation produces a level swell and the frothy mixture adequately covers and cools the 'U' tubes. However, after the pressure undershoot on the secondary side at 50 seconds the following pressure rise reduces the rate of vapour formation and the levels settle out. For the broken loop steam generator this level is around 1 metre.

At this time the power has not been scrammed, and the heat transfer to the broken loop secondary side is now insufficient to cool the primary flow. The result is a rise in the temperature of the primary flow exiting the steam generator and a corresponding fall off in the vapour flow from the broken loop side. The primary flow exit temperature rises to the inlet temperature. This is illustrated below.

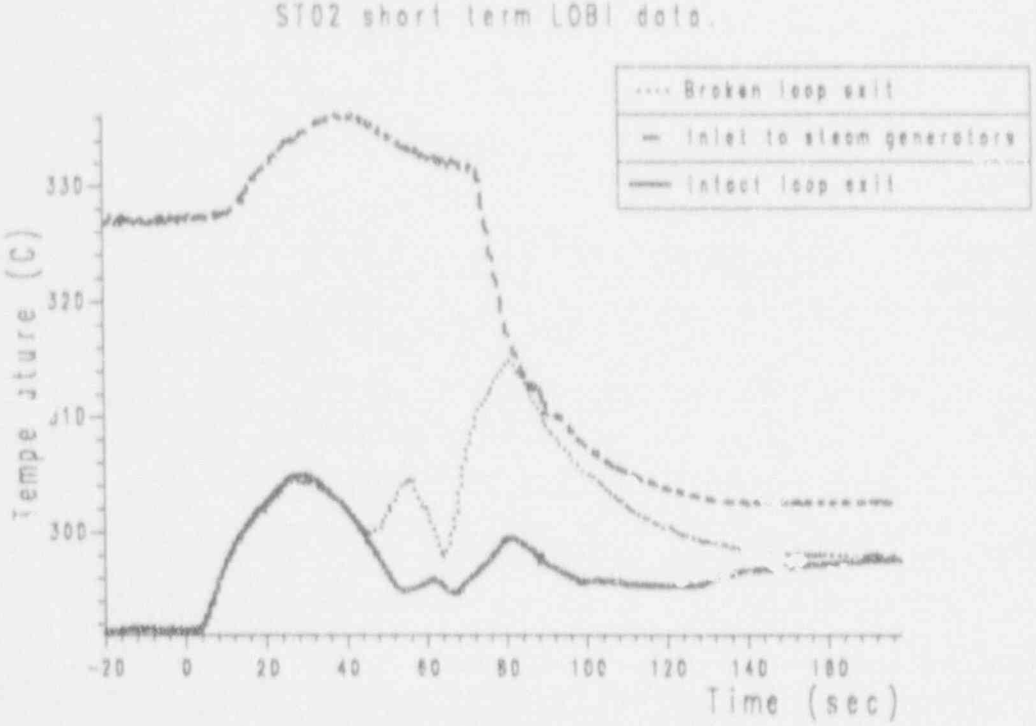

Figure 15. Primary loop temperatures: Experiment

After the scram at 70 seconds, the temperature drops back towards the secondary side saturation temperature.

On the intact loop side, starting with a larger inventory, the 'U' tubes are never uncovered sufficiently to degrade the heat transfer, and the exit temperature follows the secondary side saturation temperature throughout this time.

To show this effect, the calculation would have to begin with about the correct mass on the broken loop secondary side, then the mass vented through the relief valves would need to be correctly modelled and finally the point at which the froth level collapses and the heat transfer degrades would need to be accurately predicted.

The Figure 16 on page 19 shows the comparison, and it can be seen that RELAP does a remarkably good job, especially considering the uncertainties in some of the initial conditions.

To indicate that the result is due to the correct mechanism, Figure 17 on page 20 shows the steam flows predicted to be exiting the steam generators. Remembering that the two steam generators are tied together via a common header, and that the relief valves are still open at 65 seconds, it is clear that the fall off in steam flow from the broken loop steam generator must be due to the heat transfer degradation.

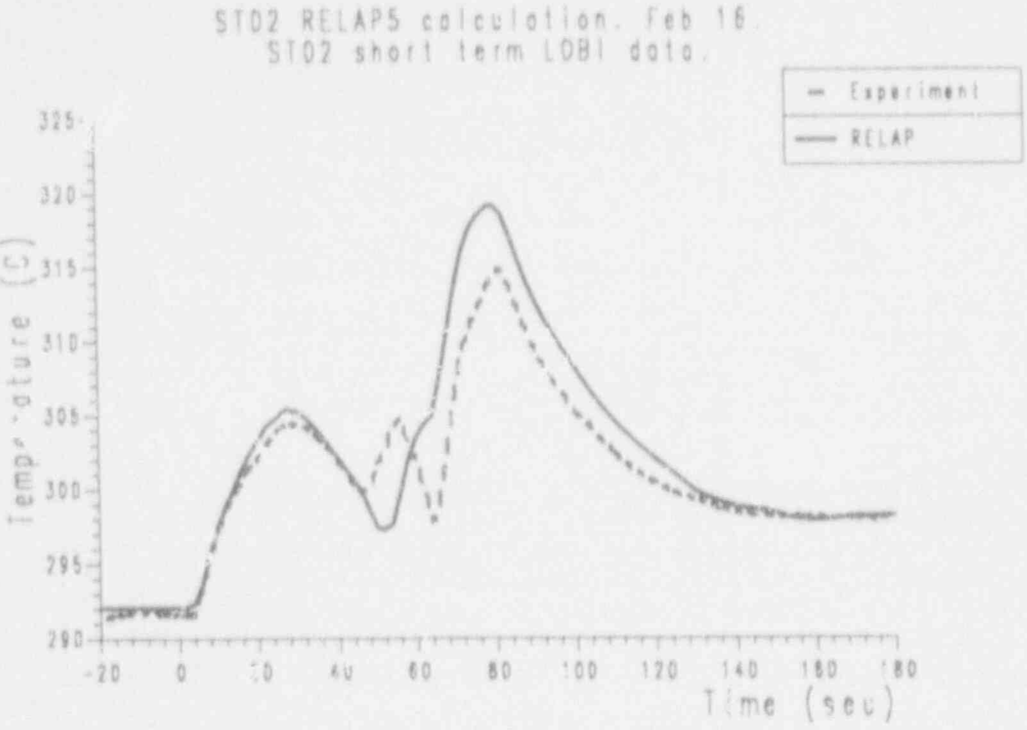

Figure 16. Exit temperature from the broken loop steam generator: Experiment and prediction

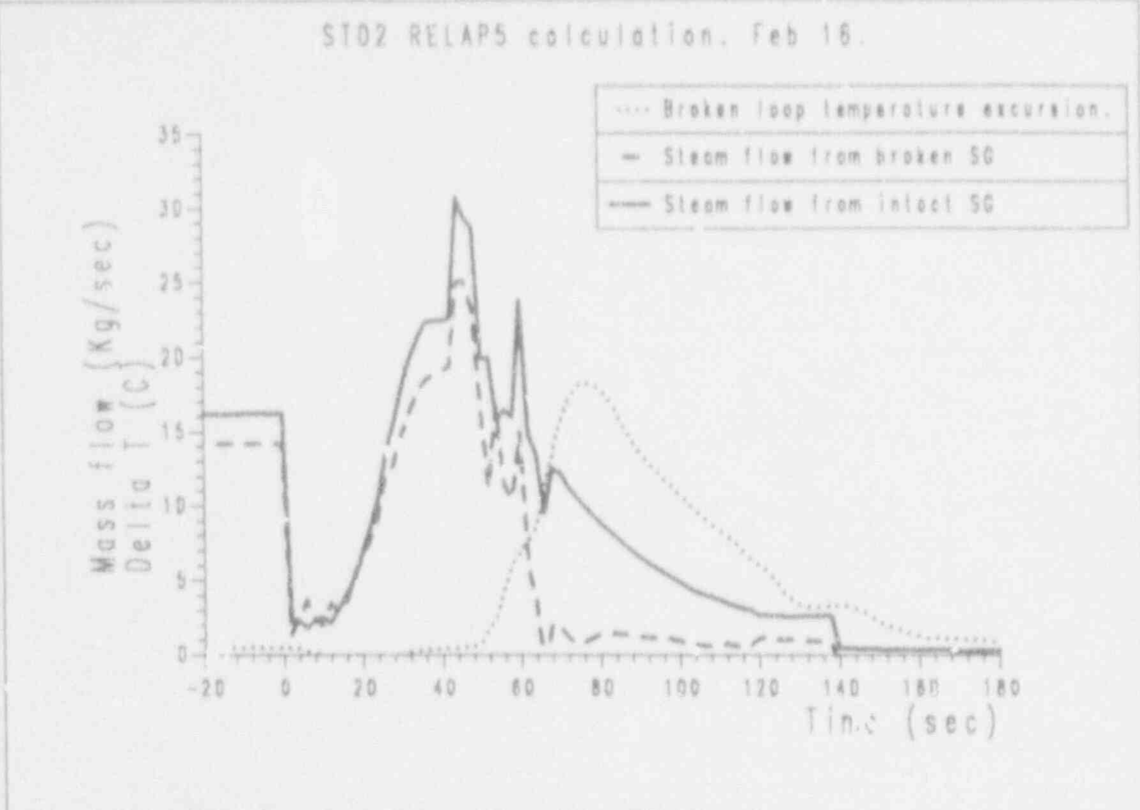

Figure 17. **Steam flows from the secondary side:** RELAP prediction.

Overlaid on this plot is the temperature excursion seen at the broken loop steam generator exit, produced as the difference between the exit temperatures in both loops. This makes the relation between the two events very obvious.

One result indicated by the above is that the void distribution in the broken loop steam generator predicted by RELAP must match the experimental distribution fairly well. This is also born out by the data.

It is also encouraging that the broken loop steam generator initial inventory is close enough to produce this effect, as the operation with a very reduced level could affect the recirculation ratio substantially and give rise to a further error.

2.2.3.4.3 Pressurizer stratification. The heatups and cooldowns of the primary side cause inflows and outflows from the pressurizer. The temperature of the loop fluid is some 30 degrees below the saturated fluid temperature in the pressurizer and is injected at the bottom. In the test thermocouples show that this insurged fluid remains, almost unmixed, at the bottom of the pressurizer, and is then mostly expelled again during the subsequent outsurge, leaving the pressurizer with an enthalpy similar to that before the surge.

This affects the system response. If the insurge had mixed with the pressurizer fluid, it would have lowered the overall temperature, reduced the pressurizer pressure and incidentally therefore increased the surge flow. Also after the outsurge, the system pressure is controlled by the fluid saturation temperature in the pressurizer. If this is a mixed temperature then the pressure reached will be lower than if it is the unmixed fluid above the cold insurge which controls the pressure.

The overall agreement achieved by RELAP for the pressure response argues that this was well modelled. Below is the RELAP prediction of this effect.

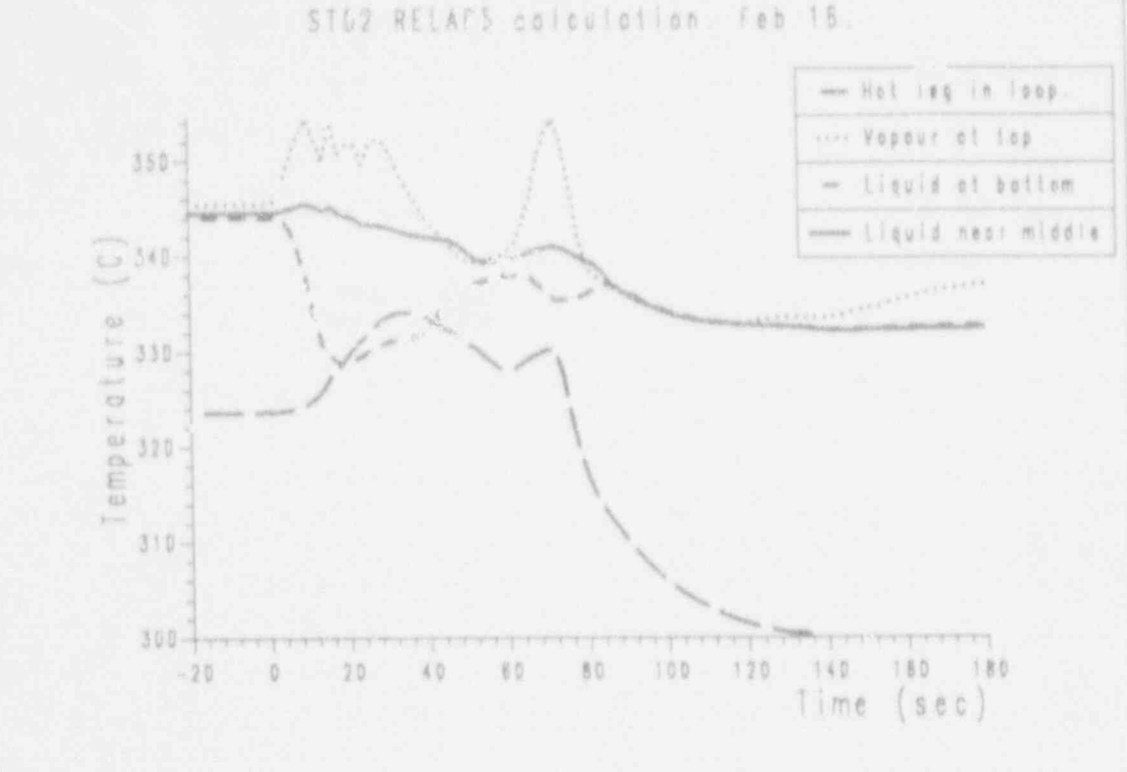

Figure 18. **Pressurizer stratification:** RELAP prediction.

RELAP clearly calculates the stratification. The vapour temperature follows the pressure, as would be expected, and responds to the compression caused by the insurge. At the middle elevation, just below the interface, the fluid temperature is only slightly affected by the cold insurge while at the bottom the temperature drops to that of the loops. In fact it drops below the loop temperature at one point as the loop temperatures continue rising after the insurge diminishes.

With the relief valves open the pressure falls to the point where the vapour and liquid temperatures coincide, and at this point generation of vapour from flashing liquid slows and controls the pressure.

The outsurge of fluid which accompanies the fall in primary temperature correctly removes the bulk of the cold water which had been carried in with the insurge and thus the bottom of the pressurizer regains its initial temperature.

Overall then the RELAP code appears to do a very good job of dealing with the stratified conditions, but it must be stressed that this is based on circumstantial rather than experimental evidence.

2.2.4 The long term transient.

Following the successful calculation of the early part of the transient the remaining time was calculated with only two input changes needed. As was discussed in the overview, the LOBI operators had turned on the pressurizer heaters in an attempt to shorten the transient. This action was simulated by a trip based on the pressure at which it occurred.

Also the criterion for the start of phase three was different from the specification. This too was updated to reflect the actual initiating event.

The whole transient was then calculated with no further 'tuning'. It will be discussed in sections, using the identifying letters from Figure 3 on page 6.

2.2.4.1 The cooldown, period 'b'.

When this test was specified, the heat losses from the pressurizer were believed to be around 1 to 2 kW. Performance of the test led to the slow cooldown seen in period 'b', which was faster than expected, and consequently changed the course of the transient.

Following this test, the LOBI team performed their own post-test analysis, and based on this stated that a figure of 9 kW may be more realistic. This figure was used in the present calculation.

During this period, the system pressure is defined by the pressurizer pressure, which in turn depends on the pressurizer liquid temperature. With no interchange of fluid between the pressurizer and the main loop, the pressurizer cools slowly due to heat losses. The rate of cooling depends on these losses, the liquid inventory in the pressurizer at the start of the cooldown (the thermal inertia), and the dependence of the losses on liquid height, if any.

In the global comparison plot, Figure 5 on page 8, it is clear that RELAP is depressurizing very slightly too fast. This points to a heat loss figure of nearer 8 kW. In fact later data from LOBI have supported this figure, but the calculation was complete by then, and this was considered only a small detail.

On the secondary side the pressure is controlled at the set point during this time. Due to the way the control system was modelled the RELAP calculation has some minor oscillations superimposed on this set pressure. These in turn give rise to a rather wavy secondary side temperature in the period from 200 to 1700 seconds which in leads to the primary side temperature fluctuating. This can be seen in Figure 19 on page 23.

More important than these spurious waves, is the difference in temperature across the steam generator, and the exit temperature from it.

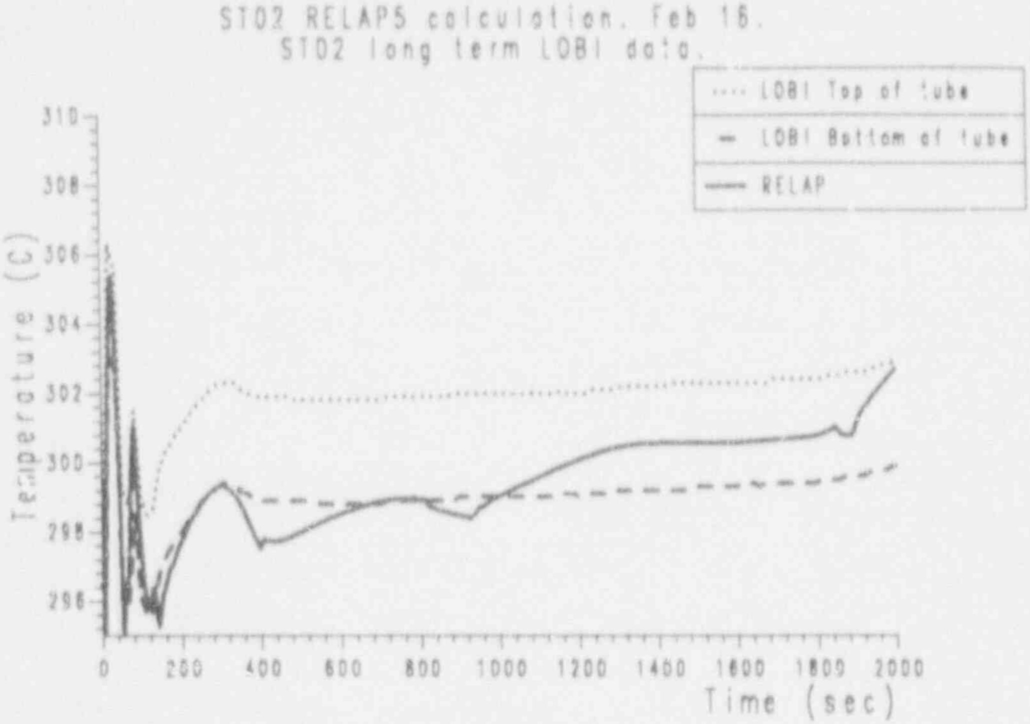

Figure 19. **Intact loop cold leg temperatures:** RELAP and LOBI data.

The exit temperature in the RELAP calculation matches the measured temperature at the bottom of the cold leg. However, it is a few degrees cooler than that seen at the top of the tube. This difference reduces towards 2000 seconds.

What is happening here is a coincidence, coupled with faulty RELAP modelling. In LOBI the pump seal water is injected down the pump shaft, and enters the loop quite cool. A thin ribbon of this fluid, washing over the thermocouple at the bottom of the tube, gives rise to the stratified temperatures seen in the LOBI measurements. The top of tube value is more correct in terms of the fully mixed temperature. It is coincidence that the RELAP cold leg temperature should match this value.

Taking the top of tube value as correct, and looking at the temperature fall passing through the steam generator it is seen in Figure 20 on page 24 that the temperature differential predicted by RELAP does match that seen in LOBI, but that the absolute value of the temperature is about 4 degrees too low.

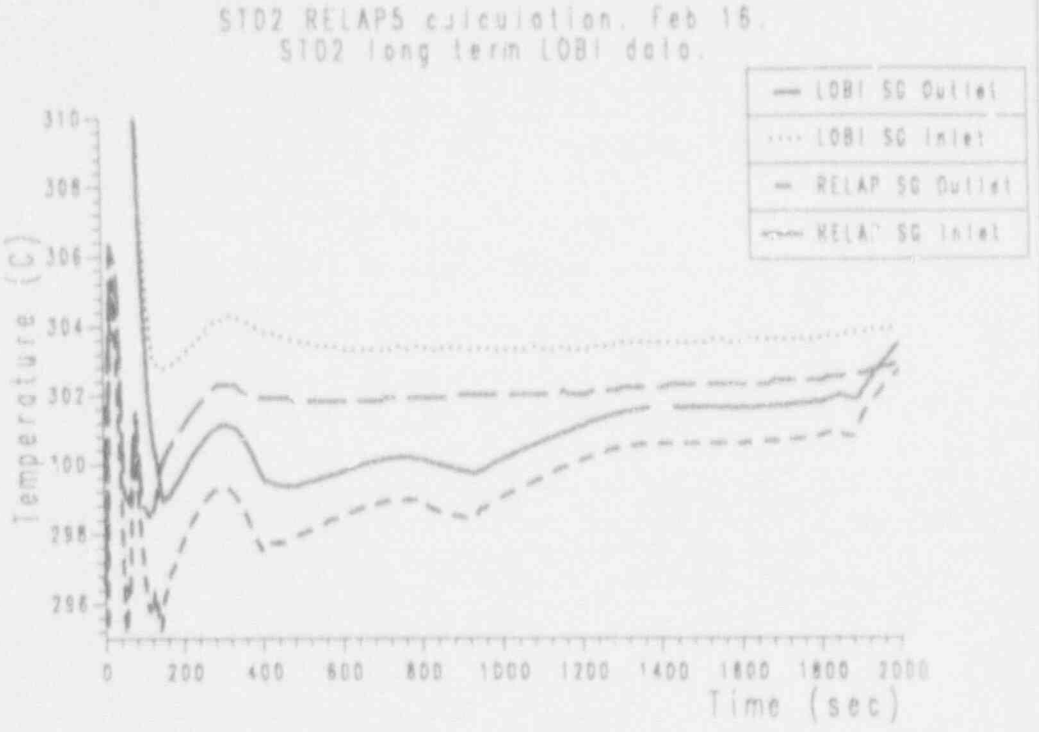

Figure 20. Temperature differential across SG: RELAP and LOBI data.

The fact that the differential is right is not surprising. Taking any given exit temperature from the steam generator the power input by the electrically heated core will raise this by a fixed amount. Thus if the core power, a given tabular input, is right, this rise must be correct.

However, the absolute value of the temperature is defined by the temperature difference between the primary side and the secondary side. This is the difference required to transfer the input core power into the secondary side, and depends on the effective heat transfer coefficient between primary and secondary. Since the secondary side temperature seen in LOBI matches that calculated by RELAP, the heat transfer coefficient in the RELAP calculation must be too high, roughly by a factor of 2.

One reason for this is the noding sizes on the secondary side. Because it was appreciated that for this test it would be important to correctly model the secondary side behaviour when there was very little water in the steam generators, the noding towards the bottom of the 'U' tubes on both the primary side and the secondary side was made quite fine, down to 0.3 m at the bottom, with a 0.7 m node above. Even this however proved too coarse.

RELAP deals with the heat transfer to heat slabs in a volume in a rather simple way, with no reference to a liquid level should one exist. This is a result of the original philosophy that finer noding would achieve better detail if needed. What happens is that the heat slabs attached to a volume are assumed to be fully wetted by a mixture with the average voidage seen in the volume. If, as if often the case, the volume is stratified then only when the voidage rises above 95 percent will the heat transfer to the liquid degrade at all. Effectively the code allows direct heat transfer from the whole slab with full wetted surface area to the liquid in the volume.

Because of this, it is not until the level falls below the volume that any real change in heat transfer is seen. An example of this can be seen in the RELAP calculation as the level in the steam generator falls into the very bottom node. Only at the very moment of the liquid crossing the node boundary does the heat transfer fall off, with consequent rise in the primary side temperature. In fact once in the bottom volume the calculation more closely approximates the LOBI results, which show a gradual decline in the ability of the secondary side to cool the primary side.

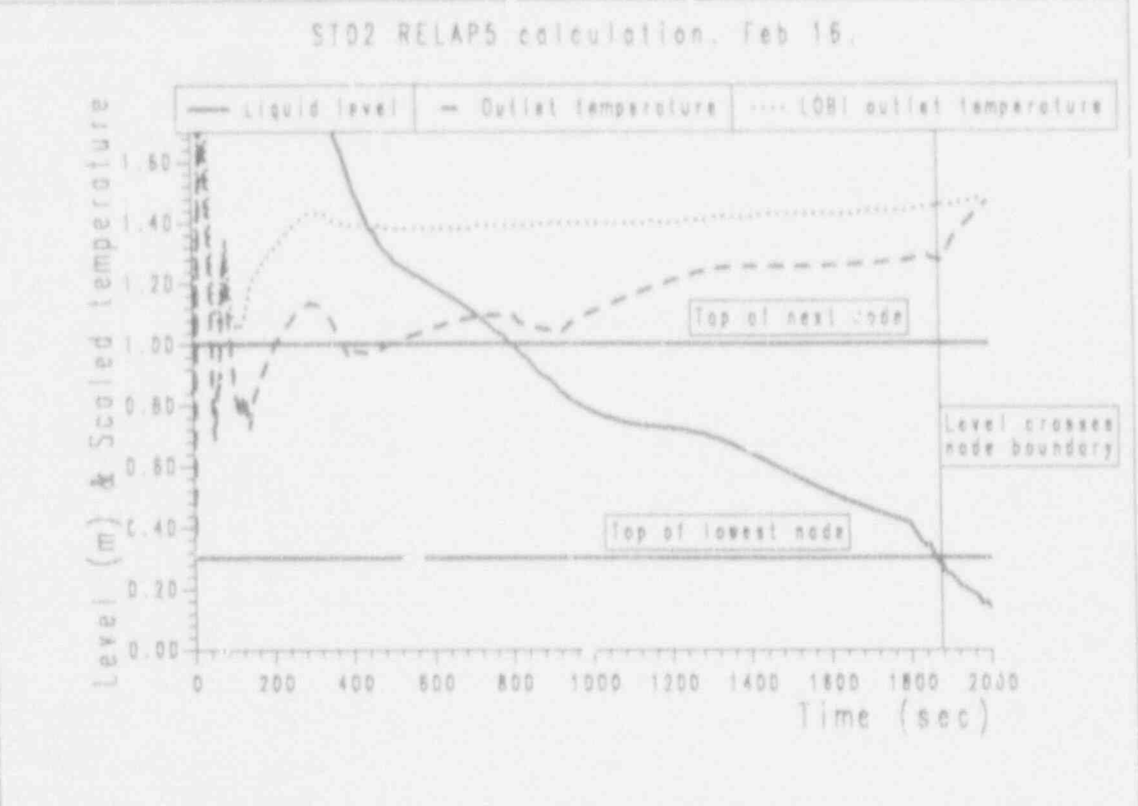

Figure 21. Level crossing volume boundary in steam generator: Effect of heat transfer.

Even with this effect allowed for, the RELAP calculation appears to overpredict the heat transfer to the secondary side, although now by a lesser extent. Interestingly, the input deck had been 'tuned' slightly to match the steady-state LOBI data by reducing the 'U' tube wall thickness and using the inter-tube gap for the hydraulic diameter. This had been done to ***reduce*** the temperature difference calculated by RELAP between primary and secondary. It is possible that this has exacerbated the current over-cooling now that the level is very low and the flow is basically stagnant. It may be concluded from this that the heat transfer to both flowing and stagnant secondary side conditions could be improved in the models used in RELAP. This is only a speculation and no further work has been done to clarify this point.

2.2.4.2 Turnaround in pressure and slow heatup, period 'c' to 'e'.

The original specification called for the auxiliary feed to be terminated when the level in the steam generator reached the 1 m mark. In the broken loop, because of the very low initial level, this point was reached at 248 seconds. In the intact loop this occurred at 1805 seconds. The effect of this was to hasten the fall of the liquid level and hence degrade the primary to secondary heat transfer, giving rise to a primary side temperature which rose more rapidly after this time.

At 'c' the falling pressurizer temperature crosses the slowly rising primary side temperature and pressure control switches to the primary saturation temperature. The pressurizer then becomes increasingly subcooled.

The calculation predicts this event slightly early, as would be expected from the overly rapid depressurization of the pressurizer. The comparison is shown on Figure 22 on page 26 below.

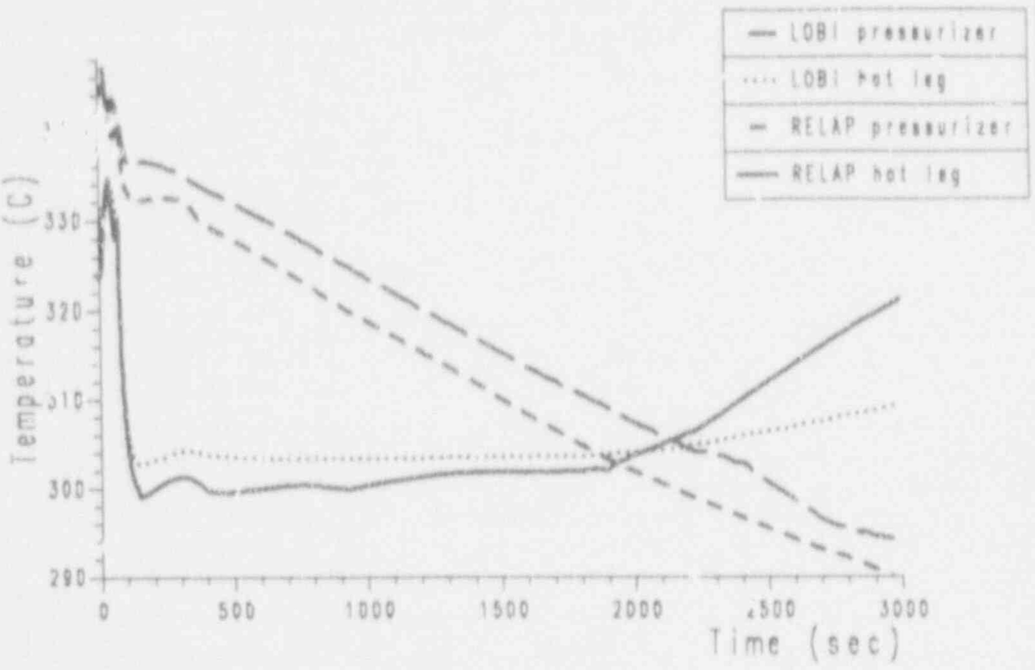

Figure 22. **Turnaround in system pressure:** Calculation and experiment.

Furthermore, the RELAP calculation had predicted a faster fall in the liquid levels in both steam generators and this had in turn speeded the primary side heatup.

By 2200 seconds in the RELAP calculation both steam generators are empty and the primary side heatup proceeds even faster. In LOBI the steam generators do not fully empty until after 3000 seconds, so the initial primary side heatup is slower. Once empty though the rates of heatup seen in LOBI and the RELAP calculation are quite different.

Although the disparate timings between the data and calculation do give rise to slightly different core powers, based on the decay curves, this is a very small effect. It amounts to about 5 kW for a 1000 seconds disparity at 2000 seconds, and reduces as time progresses. So the only explanation is that LOBI is dissipating a lot of heat which is not going into warming the primary fluid. Most evidence points to the steam generators, which have heat losses which are somewhat uncertain. A crude heat balance would indicate that some 40kW must be lost from each steam generator, to be compared with the estimated 14kW given by LOBI.

It had been known that the estimated losses may have been incorrect, and this test and others had pointed to a higher value. However the total of 80kW needed in this case is exceptionally large. It seems unreasonable to ascribe this to simple heat losses, and an alternative explanation was sought. (Subsequently, more detailed measurements by LOBI have revised the estimates upwards, but only to a total of 47kW.)

It had been noted that the derived level in the broken loop steam generator appeared to rise later in the transient. It had also seemed very slow to empty, compared to the RELAP calculation, even allowing for the possible errors in discharge through the relief valves. It seemed possible that fluid was entering the broken loop steam generator. This could be steam condensing in the steam generator and originating in the intact loop steam generator after passing along the common steam line, but two pieces of information suggest another source.

Following the performance of this test, LOBI announced that a leak had been discovered between the primary and secondary side, in the broken loop steam generator This leak was caused by one of the pressure tapping pipes which connect to the top section of the 'U' tubes. The design allows for thermal expansion by using a sliding plate system between the downcomer and riser sections of the secondary side. One of these plates had jammed, preventing the pressure tapping tube from moving together with the 'U' tubes, and resulted in the weld between 'U' tube and pressure tapping fracturing, thus giving a small primary to secondary leak.

LOBI believed this leak occured after ST-02, but this seems a very likely candidate for the extra energy loss. Even a small leak from primary to secondary would remove considerable enthalpy. A 20 gram/second leak would suffice to balance the books, and this would have the additional effect of maintaining the secondary side pressure high after the auxiliary feedwater is terminated. One of the major discrepancies between RELAP and LOBI is the secondary side response after 3000 seconds as seen in Figure 5 on page 8.

Additional support is given by the measured steam generator outlet temperatures in LOBI. Shortly after 2000 seconds the broken loop experiences a significant decrease in the exit temperature from the steam generator. This is not seen in the intact loop and could indicate the onset of the primary to secondary leak. Leaking fluid boiling off through the secondary side relief valves could remove a lot of heat, increasing the cooling of the primary side flow through the U-tubes, and hence reducing the exit temperature from the steam generator.

It was concluded that the leak discovered following the test probably occured during the test with the above consequences.

Heatup of the primary coupled with vapour formation forces liquid back into the pressurizer. The level slowly rises, and ultimately completely fills the pressurizer, making it water-solid. This is predicted by RELAP and seen in the LOBI data, with the timings being different dependent on the heatup rates, but the general agreement being very good.

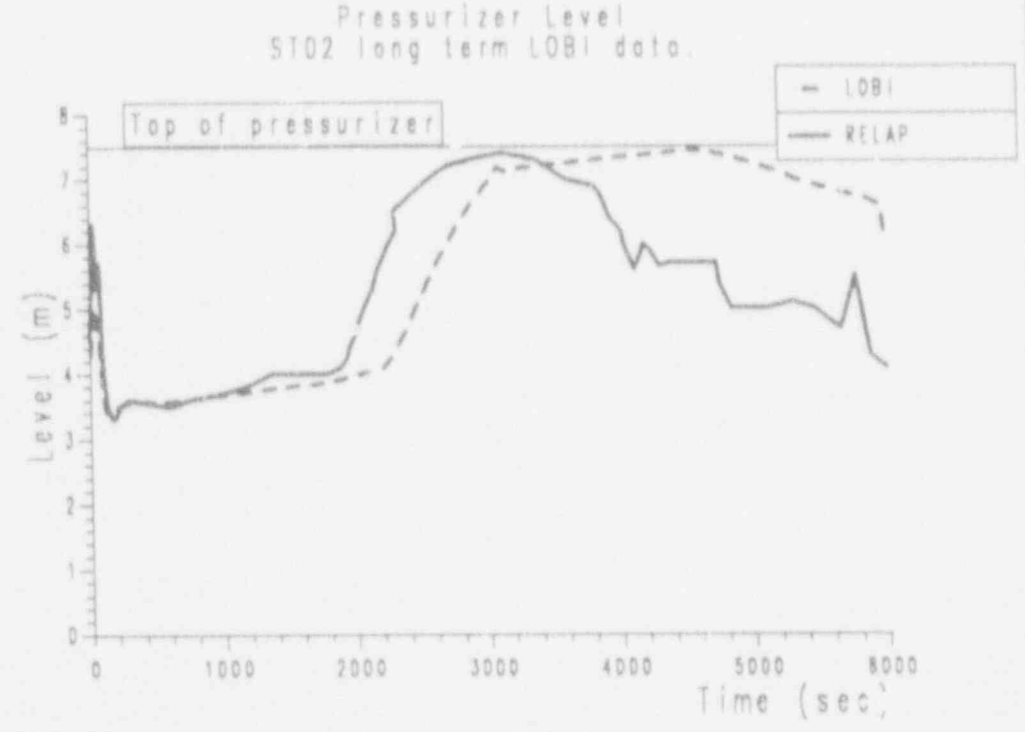

Figure 23. **Pressurizer level:** Calculation and experiment

Because of the modelled steam generator heat losses being too low, and the further effect of the leak, the primary system heats up far too quickly in the RELAP prediction. LOBI operators turned on the pressurizer heaters in the test, and this had been modelled based on a pressure trip, so the subsequent RELAP calculation would show all events following initiation of pressurizer heating occuring a fixed time early. To allow for this subsequent plots of primary parameters will be offset.

As the pressurizer heats up, the subcooling is reduced and finally is lost altogether. Boiling in the pressurizer again controls the system pressure, which rises much more rapidly from 'e' and a vapour bubble is re-established in the top of the pressurizer.

2.2.4.3 Pressure spike at 'f', and beyond.

As mentioned in the overview, section 2.2.2, the primary side keeps heating up at the same rate while the pressurizer re-establishes primary subcooling. The spike in pressure seen at 'f' is superimposed on the overall temperature transient.

Because the temperature is rising more rapidly in the RELAP calculation, this underlying transient is different, although the pressure spike, depending only on pressurizer input power, is the same. The Figure 24 indicates this.

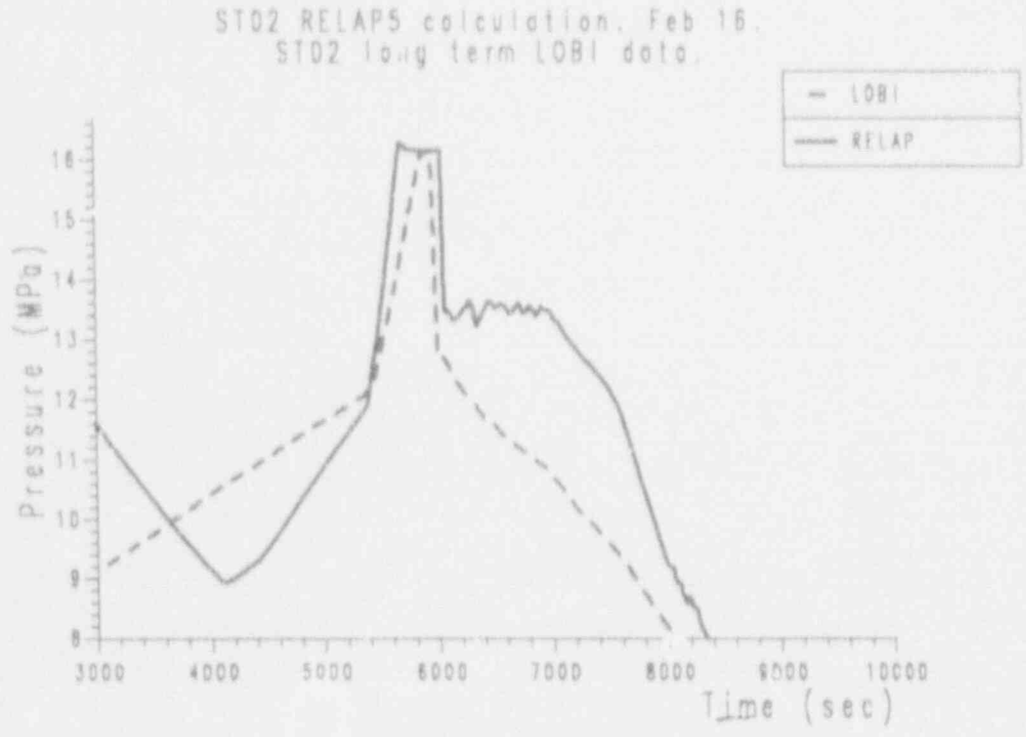

Figure 24. Pressurizer heatup: Calculation and experiment.

The flatter top on the RELAP calculation is simply due to trip which opened the pressurizer PORV being slightly later in the RELAP model than in the test. Because the large relief valve did not open, the small control valve vented mass to limit the pressurizer pressure.

With the PORV open there is a rapid depressurization to the primary saturation temperature. The pumps were tripped at this time and forced circulation rapidly ceases. Flashing of liquid to vapour slows the pressure fall at 'g', but does not halt it in the LOBI test.

In RELAP, there is a considerable period when the pressure hangs at the initial saturation point before falling off. This could be influenced by the extra heat losses in LOBI which had slowed the heatup, now helping to remove heat which would otherwise generate vapour and slow the fall. There is however another possibility, that of erroneous level swell.

Examination of the pressurizer collapsed level, Figure 25, shows that although the agreement is good following the PORV opening, and during the period of the RELAP pressure plateau, there is a calculated level fall in RELAP not seen in the LOBI data.

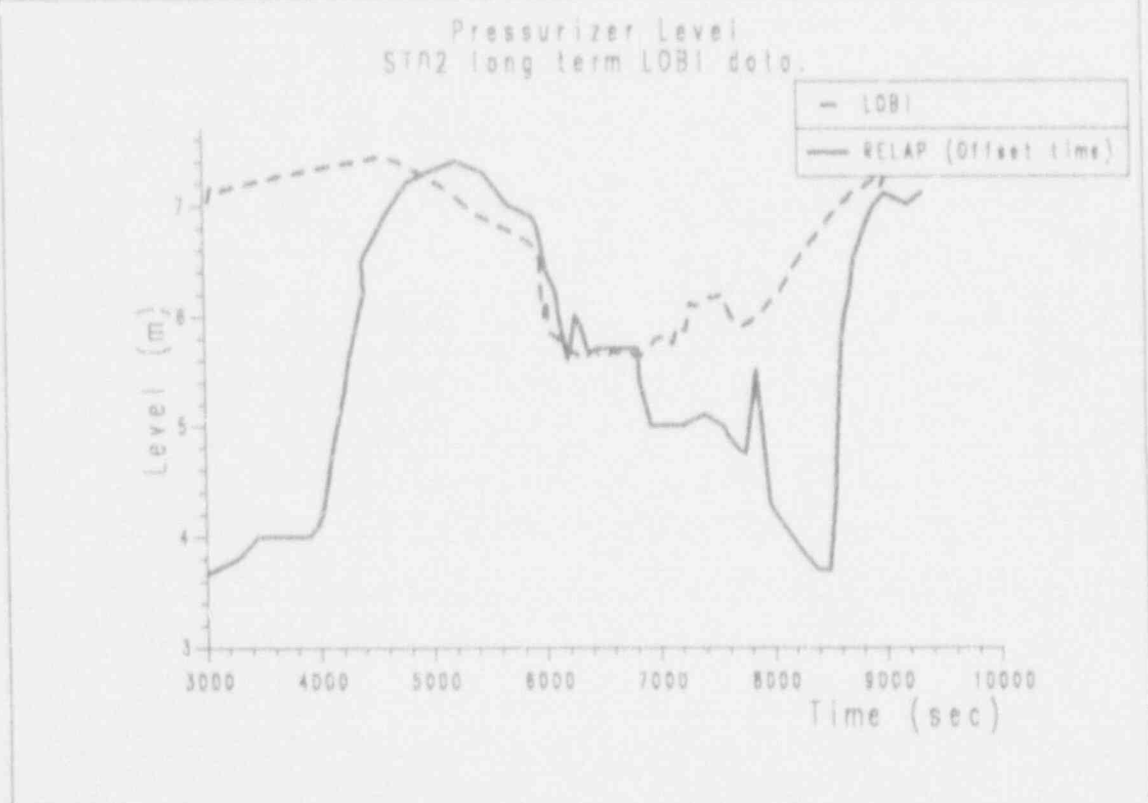

Figure 25. Pressurizer level: Calculation and experiment.

The measured mass flow through the PORV agreed approximately with the RELAP prediction early on, but there is a possibility that the upstream conditions are different.

RELAP has been found in previous studies to overpredict the voidage seen in basically stagnant liquid pools, especially in rod and tube bundles. This is a consequence of the interfacial drag models, and is partially caused by the lack of profile slip in the RELAP equations (Scriven 87 and Putney 87).

In the pressurizer the void distribution will control the conditions in the top most volume, and in RELAP this results in a pressurizer full of frothy fluid. This fluid is discharged through the PORV. Only when voiding reduces to the point where the topmost volume is able to discharge steam does the pressure fall rapidly. The effect can be seen in Figure 26 on page 30.

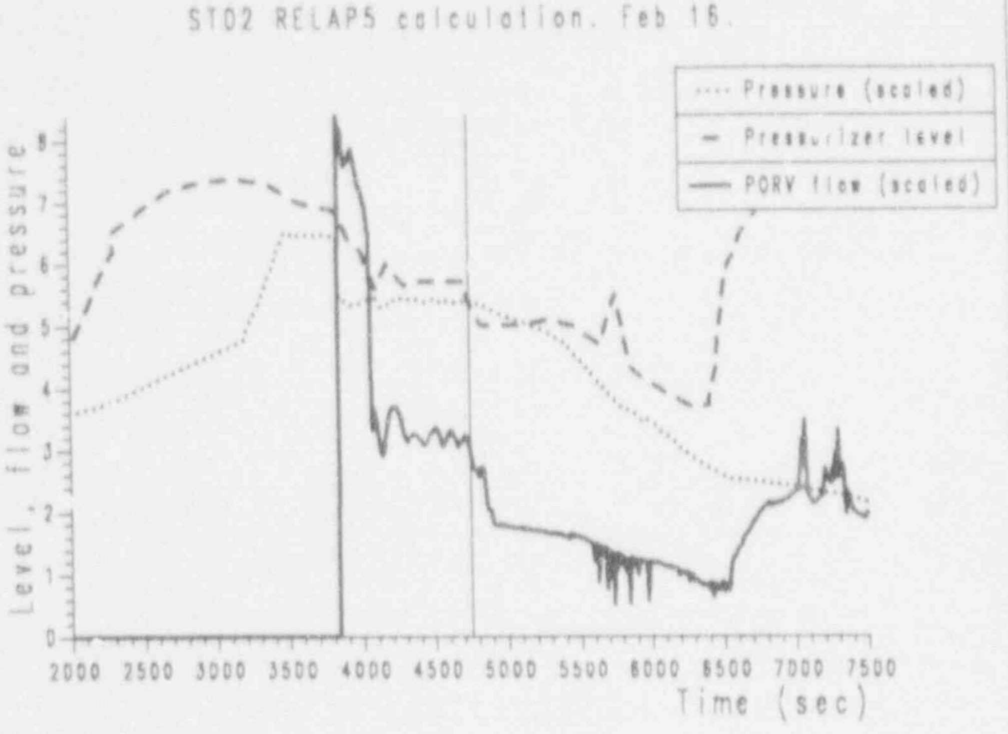

Figure 26. Conditions in the pressurizer

In this figure, the pressurizer collapsed level remains at around 5.6 metres during the pressure plateau. With a pressurizer voidage [illegible] percent throughout this corresponds to a froth level filling the top volume.

At the end of the pressure plateau the mass flow through the PORV drops off, indicating a change to mostly vapour in the upstream donor conditions and the collapsed level also shows a sharp drop.

There is no data from LOBI which allows an estimate to be made of the froth level in the pressurizer, or of the upstream break conditions. Therefore the above proposal cannot be validated, and remains a speculation.

The remaining calculated period shows reasonable agreement with the LOBI data on the primary side, but by now, with the substantial divergence on the secondary side, there is no indication of the decoupling between primary and secondary which is seen in LOBI when the primary voiding drains the 'U' tubes at around 6100 seconds. The excess voiding on the primary side in the RELAP calculation recovers after the high pressure injection system comes in, and following this the prediction does show loop conditions slowly becoming stable as the bleed and feed successfully removes the decay heat.

The accumulated divergences make detailed comparisons very difficult in this period.

The calculation finally terminated abnormally with the pressure near 5 MPa. Because of the poor agreement with secondary side conditions and the dependence of later events on these conditions, no effort was made to resolve the failure and calculate the transient further.

3.0 Conclusions

The ST-02 transient required a great deal of effort to calculate, not due to code problems but to LOBI specific effects and actions which were not well understood prior to this test.

- The test was performed with numerous of the specified boundary conditions unfulfilled thus making comparisons with pre-test calculations impossible.

- The post-test analysis was severely handicapped by lack of accurate data for important boundary conditions and operator actions. To achieve a reasonable calculation many guesses had to be made about inventories, valve openings and secondary side leaks.

- The major parameters of this test were unduly influenced by very small variations in facility specific features, many of which, such as pressurizer heat losses, are not well understood. This makes global comparisons between experiment and calculation less than straightforward.

- In general the experiment was poor from the point of code assessment, as many areas in which the results differ could be ascribed to unknown boundary effects or incorrect modelling due to incomplete input data.

- Globally RELAP performed well, and in some instances produced detailed predictions of effects reliant on sensitive phenomena. Some features of code modelling were tested, and the results were:

    1. The lack of heat transfer partitioning based on the liquid level in a volume gave rise to some erroneous behaviour. This could be a topic for code enhancements.

    2. There is a suggestion that the heat transfer to the secondary side under stagnant conditions is overpredicted, especially when the level is very low. This could lead to a lack of conservatism in calculation where the secondary side heat sink has a major effect in controlling the primary excursion. Evidence should be sought to confirm this possibility.

    3. The known interfacial drag problems of excess voidage in boiling pools may have given rise to erroneous level swell in the pressurizer and consequently incorrect discharge from the PORV.

- The overall picture is that there are too many uncertainties to admit meaningful comparisons in many instances. The code can be made to match the data, if enough time is taken to adjust all the uncertain inputs to give a best fit. This is however a pointless exercise.

- The greatest benefit of this test seems to be the better characterization of the LOBI loop, especially the valve responses and pressurizer heat losses, and to point out the need for further experiments on LOBI to improve values for secondary side heat losses.

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11. ABSTRACT *(200 words or less)*

The experiment ST-02 (later renamed BT-00) is one of a series of Special Transient tests being performed on the electrically heated LOBI facility at Ispra in Italy. This test was designed to simulate a loss of main feedwater transient leading via a steam generator dryout to a long term cooldown using bleed and feed. The RELAP5/MOD2 code has been chosen by the Board for assessment work on the Sizewell Pre-Operation Safety Report. It was originally designed for Loss of Coolant Accidents, but is now finding wider applications. RELAP5/MOD1 was used for a pre-test calculation, and RELAP5/MOD2 for the detailed post-test analysis. This was to allow cross-code comparisons, assess the possibility of using RELAP5 for pressurized transients and because the final phase of bleed and feed which occurs in test ST02 is more representative of Small Break tran[illegible] essurized Faults. This report documents the results of this calculation and comparisons with the test data. Af[illegible] for test conditions and events outside the original specification the RELAP5/MOD2 code was found to perform ra[illegible]

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