FAILURE PROPAGATION TESTS AND ANALYSIS AT PNC

H. TANABE, O. MIYAKE, Y. DAIGO, M. SATO
Power Reactor and Nuclear Fuel Development Corporation,

K. FUJII
Kawasaki Heavy Industries, Ltd,

Japan

ABSTRACT

Failure propagation tests have been conducted using the Large Leak Sodium Water Reaction Test Rig (SWAT-1) and the Steam Generator Safety Test Facility (SWAT-3) at PNC in order to establish the safety design of the LMFBR prototype Monju steam generators. Test objectives are to provide data for selecting a design basis leak (DBL), data on the time history of failure propagations, data on the mechanism of the failures, and data on re-use of tubes in the steam generators that have suffered leaks.

Eighteen fundamental tests have been performed in an intermediate leak region using the SWAT-1 test rig, and ten failure propagation tests have been conducted in the region from a small leak to a large leak using the SWAT-3 test facility. From the test results it was concluded that a dominant mechanism was tube wastage, and it took more than one minutes until each failure propagation occurred. Also, the total leak rate in full sequence simulation tests including a water dump was far less than that of one double-ended-guillotine (DEG) failure.

Using such experimental data, a computer code, LEAP (Leak Enlargement and Propagaion), has been developed for the purpose of estimating the possible maximum leak rate due to failure propagation.

This paper describes the results of the failure propagation tests and the model structure and validation studies of the LEAP code.

1.0 INTRODUCTION

In an LMFBR steam generator, chemically reactive sodium and water are used as the heat transfer media. For this reason, the safety of the steam generator, particularly the protection against sodium-water reactions, is a very important problem. It is necessary to confirm the reliability of an LMFBR plant with regard to its availability. A research program of steam generator safety and reliability has been conducted for more than ten years in Japan, and results are reflected in the steam generator design.

Generally, the growth behavior of the sodium-water reaction accident can be described as follows: A leak initiates as a micro-leak due to a faulty weld or other imperfection, and self-enlargement would increase the leak rate to a small or intermediate leak level. Moreover, if no action were taken against the leak, it might grow to a large leak level due to failure propagation phenomena.

In the actual steam generator system, the leak could be detected at an early stage and the related operations, including emergency water blowdown, could prevent failure propagation. However, the time required for the operations might allow failure propagation to a certain degree; thus the extent of failure propagation should be estimated in advance for the steam generator design. This is the design basis leak (DBL) which is the basis of the steam generator system design and must be chosen prudently with regard to the results of experimental studies of the sodium-water reactions and the design capability of the related equipments.

Many experimental studies have been performed on the sodium-water reaction phenomena from the micro-leak to the large leak regions using the sodium-water reaction test facilities: the Large Leak Sodium-Water Reaction Test Rig (SWAT-1). the Small Leak Sodium-Water Reaction Test Loop (SWAT-2), the Steam Generator Safety Test Facility (SWAT-3), and the Micro Leak Test Rig (SWAT-4) at PNC in Japan. Particularly, experiments intended to investigate the failure propagation phenomena have been underway using SWAT-1 and SWAT-3 as described in Chapters 2 and 3, respectively. Fig. 1.1 shows a schedule of the failure propagation tests.

A computer code LEAP has been developed to estimate the maximum leak rate due to leak propagation. The validation studies have been carried out by comparing with the SWAT-3 experimental data mentioned above, and it has been confirmed that the LEAP calculations estimate the extent of the failure propagation with enough conservatism. The outline of the LEAP code and its analysis are described in Chapter 6.

2.0 TEST OBJECTIVES

The more detailed test objectives are listed below for the propagation tests of both SWAT-1 and SWAT-3 to accomplish the purposes described above.

2.1 Objectives of SWAT-1 Tests

1. Obtain data on secondary failure time in the intermediate leak region.
2. Obtain data on the shape and the magnitude of the secondary failures.
3. Determine the mechanism of the failures.

4. Obtain data on the extent of the damaged area.

2.2 Objectives of SWAT-3 Tests

1. Provide data on time hisory of the failure propagations.
2. Provide data on the size of failure.
3. Define the potential for tube failure due to overheating.
4. Provide data on re-use of the tubes in the failed steam generators.
5. Provide data to validate the LEAP code.

3.0 SWAT-1 TESTS

3.1 Test Rig

The SWAT-1 test rig consists of a test vessel of 400 mm diameter which contains about 150 kg of sodium, a water supply system, and a pressure relief system. A tube bundle that contained about thirty tubes was suspended in the reaction vessel. One of the tube bundle configurations is shown in Figure 3.1. The material of the tubes was 2-1/4Cr-1Mo steel, the same as in the design of the Monju evaporators. Though the real tubes of the Monju design are helically coiled, straight tubes were used in the tests to provide advantages for the wastage measurement. Nitrogen gas was applied to the inside of several main target tubes so as to simulate the tube bursting. Other tubes had both ends open.

More than fifty thermocouples were distributed around the tubes for the measurement of the reaction temperature. After each test the internals were pulled out from the test vessel and were disassembled to tubes. The state of the wastage was recorded by an auto-measuring and plotting system. Metallurgical examinations were also conducted.

3.2 Test Conditions

The conditions of the eighteen tests are outlined in Table 3.1. To achieve the objectives described in the previous chapter, the following test parameters were selected as variables.

1. Leak size - from 0.5 mm to 3.0 mm leak nozzle diameters that resulted in water leak rates of 10 g/sec to 200 g/sec.
2. L/D - L means the distance between the leak nozzle and a target tube. D means the leak nozzle diameter. L/D was chosen from the range of 10 - 100.
3. Collision angle - an angle between the direction of the leak jet and the surface of the target tube was chosen from the range of 0 - 90 deg.
4. Water/steam condition - saturated or subcooled.
5. Sodium conditions - stagnant, and the temperature was in the range of 330 to 410°C.

3.3 Test Results

Fig. 3.2 shows the status of tube damages in Run 4101 to explain typical results of the SWAT-1 failure propagation tests. The water leak rate of the test was 194 g/sec that was the largest value among the series of tests. The direction of the leak jet was towards the left side of Tube 18. Tube 21 failed at 48 sec after the injection and then the injection was stopped immediately. Though only one tube failed, several tubes were found to be damaged as badly as Tube 21 after the internals were disassembled.

Main results obtained from the series of tests in SWAT-1 are as indicated below:

1. The wastage rate depends on L/D and has a maximum value of 7×10^{-2} mm/sec at L/D = 20 - 30.
2. The time of the secondary failure does not depend on the water leak rate because several tubes are simultaneously exposed to the flame jet in the intermediate leak region and at least one tube has the L/D value below 50 which provides a wastage rate of more than 6×10^{-2} mm/sec.
3. The maximum diameter of penetratatin holes obtained for the gas tubes is 19 mm.
4. A dominant mechanism of the secondary failures is not overheating but wastage when the water leak rate is less than 200 g/sec.
5. There is no difference of wastage rate between base metal of 2-1/4Cr-1Mo and its weld part. (See Fig. 3.3)
6. The wastage damage due to water leak into cover gas space is slight.
7. Heat tranfer coefficient of tube outer surface in the sodium-water reaction zone was evaluated.

4.0 SWAT-3 TESTS

The SWAT-3 test facility was chosen both for the fundamental tests, where the water leak rate was more than 200 g/sec, and for the demonstrational tests of the sequential failure propagation. The diameter of the SWAT-3 evaporator is about 2/5 of that of the reference Monju design. In the SWAT-3 failure propagation tests, tube specifications such as the size, the material, and the arrangement were chosen so as to provide a much more explicit simulation of the Monju design. In the initial conditions, main target tubes were filled with water or nitrogen gas pressurized up to about 150 ata (15 MPa). Ten tests have been conducted so far changing the conditions such as the initial leak rate, the direction of the leak jet, the phase of water, etc.

4.1 Test Facility

The SWAT-3 test facility used for the large leak tests of Runs 1 through 7 was modified for the failure propagation tests. Major changes were made in the internals and the water injection line.

1) Internals

Internals of Runs 8 through 10 are shown in Fig. 4.1. In Runs 11 through 13 they were also in a vertical row though the detailed tube configurations, such as tube size, pitch and arrangement, were different from those of Runs 8 through 10. In Runs 14 through 17 the internals consisted of a single test unit because the water injection line or N_2 gas supply lines for target tubes became complicated as described later.

2) Tube

Main specifications of the tubes are indicated in Table 4.1. All the failure propagation tests in SWAT-3 simulated the conditions of the evaporators; therefore 2-1/4Cr-1Mo steel was chosen as the tube material. In Runs 8 through 10 tubes of 25.4 mm OD were used but tubes of 31.8 mm OD have been used in Runs 11 through 17 in accordance with the specification change of the Monju steam generators. Hence the total number of tubes in a test decreased since Run 11. The nominal wall thickness of these tubes was 3.2 mm for Runs 8 through 10 and 3.8 mm for Runs 11 through 15. These tubes were used without reducing the corrosion allowance. To investigate the potential of overheating failure, the wall thickness of Runs 16 and 17 was reduced to 3.12 mm by removing the corrosion allowance. All of these tubes were straight so that the state of wastage could be measured easily and precisely. All tubes in Runs 14 and 15 were filled with water, though in other tests only several tubes were water-filled.

3) Water injection line

In Runs 8 through 13 the water injection line was modified so that three injection tests could be performed in one operation of SWAT-3. The line branched into three outside the evaporator, and each line was connected to the initial leak tube and the other water-filled tubes inside the evaporator. In Runs 14 and 15 all tubes were designed to be filled with water to provide a better simulation of the Monju steam generators. In Runs 16 and 17 twenty four gas supply lines were provided to measure tube failure times. As these test articles became more complicated especially inside the evaporator, Runs 14 through 17 were carried out independently with a single water injection line. In Runs 8 through 16, the water in the tubes was stagnant. Under this condition, there is a possibility that all the water in the tubes may turn into steam due to a sodium-water reaction heat. The stagnant steam has little cooling effect to the tubes, so the temperature of the tubes might become very high. In Run 17, therefore, water was designed to flow in the target tubes to simulate the operating conditions of the actual plant.

4.2 Test Conditions

Test conditions of the failure propagations in SWAT-3 are summaried in Table 4.2. The minimum value of the initial water leak rates was 6.8 g/sec in Run 9, and the maximum value was 2200 g/sec in Run 16. The water in the supply tank was saturated except Runs 14 and 17. These were subcooled, but the pressures were about 150 ata (15 MPa) in all tests.

The sodium was stagnant, and the almost same temperature as that of water was selected so as to prevent heat transfer from sodium to water. The discrepancy of the soidum temperatures between these tests and the Monju design was considered insignificant because from the SWAT-1 data it was concluded that the initial sodium temperature did not affect the wastage phenomena in the region of the intermediate and large leaks. The targets of each test are as described below:

Runs 8 - 10 :	As they were the first sequential failure propagation tests, the initial leak rates were selected from a wide range, that is, intermediate, small and relatively large leak rate for Runs 8 through 10, respectively. That of Run 10 was expected to cover the lacking area which the series of SWAT-1 tests could not fulfill because of their size limitation. As the secondary failure of Run 10 was expected to become too large, target tubes were not filled with water but with nitrogen gas.
Runs 11 - 13 :	According to the specification compatibility with Monju steam generators, tubes were changed to larger ones. The initial leak rates of Runs 11 through 13 were in the regions of the small, intermediate, and large leak, respectively. Examination of the possibility of tube failure due to overheating was one of the most important objects in Run-13.
Runs 14, 15 :	In accordance with the operational conditions of Monju steam generators during sodium-water reaction accidents, these tests were carried out to simulate the failure propagation phenomena from the beginning of the initial leak to the end of the water dump from the damaged steam generator. In order to examine the effect of the water/steam conditions on the propagation phenomena, they were chosen to be subcooled and saturated in Runs 14 and 15, respectively, and all of fifty-six tubes were filled with water from the same water supply tank.
Runs 16, 17 :	As there were few wastage data for the leak rate from 1 to 6.7 kg/sec, the initial leak rate was decided to be about 3 kg/sec to cover the whole wastage data. This value seemed to be suitable to obtain data for the overheating tube failure. The water/steam conditions were selected to be saturated and subcooled in Runs 16 and 17, respectively.

4.3 Test Results

The results of the SWAT-3 failure propagation tests are summarized in Table 4.3. Those of Run 11 were deleted from this table since water could not be injected on accout of a malfunction of the injection system. In Runs 9 and 17 no secondary failure occurred during the 36 minutes and 1 minute of injection, respectively.

In Runs 10 and 13, whose leak rates were relatively large, the water injection was stopped immediately after the occurrence of a second failure, and in Runs 8 and 12, the valves were closed after that of a third failure. In Runs 14 and 15 at least four propagations were observed before the initiation of the water dump, and one or more failures occurred during water dump of the water supply tank.

Results of Run 12 should be discussed as a typical case of propagation phenomena. The tube configuration is shown in Fig. 4.3. The injection was initiated from the leak nozzle of 1.5 mm diameter which would simulate the failure propagation from the intermediate leak region. Tube 142 is the initial leak tube whose nozzle was directed to Tube 119.

A second failure occurred on Tube 127 at 74 seconds after the injection. A third failure occurred on Tube 142 at 145 seconds. The resulting water leak rate increased step by step, that is, from 87 g/sec to 260 g/sec and to 1,460 g/sec. Besides these tubes, No. 134 failed, though the penetrated hole was so small that the occurrence time of the failure could not be detected. A gas-filled tube, No.135, also failed at 134 seconds.

In Run 16, fifty tubes were filled with nitrogen gas at 151 ata in the initial conditions. The pressure was not controlled to increase the possibility of tube bursting. The gas pressure increased with the tube temperature due to the sodium-water reaction heat. When the gas pressure reached 185 to 213 ata, which is much higher than actual operating pressure, twenty-five tubes burst. On the other hand, in Run 17, no tube failure occurred during the water injection because the inner pressures were fixed at about 130 ata which was the same steam/water pressure with 30 % load operation mode of the Monju steam generators.

Leak progressions of the SWAT-3 failure propagtion tests are shown in Fig. 4.2. It shows that it took about one minute for each failure propagation in the early stage to occur, and that the leak rate of 10 - 100 g/sec as the initial value developed more than 1 kg/sec in a few minutes by propagations. Moreover, in both Runs 14 and 15, the failure during the water dump brought about a peak value of water leak rate.

5.0 Evaluation of SWAT-1 and SWAT-3 Test Data

In the present chapter, the results of failure propagation tests in SWAT-1 and SWAT-3 are discussed in detail, considering other experimental data.

5.1 Wastage Rate

In order to evaluate generally the time for tube failure, the wastage rate should be compared because tube-wall thickness are sometimes different from each other. The relations between the maximum wastage rate and the water leak rate are shown in Fig. 5.1. The dots mean the data of SWAT-1, 2, and 3, and the lines mean the empirical formulas conservatively derived from the data.

5.2 Size of Penetration

Generally speaking, a failure propagation tends to magnify the newly penetrated hole in comparison with the precursor hole. For the purpose of examining this tendency, the relation between the diameter of secondary failure and that of the precursor hole is shown in Fig. 5.2.

Failures are classified into three types: pit, toroidal, and burst. The pit type of failure might occur in such circumstances that a limited area of a tube would be damaged by wastage in the small leak region. The toroidal type is seen in the case that the flame jet would erode the target tube toroidally in the small or intermediate leak region. The burst type is the failure that occurs when the tubes are exposed to a relatively large leak jet, the wall thins in a wide area, and the tube splits in the axial direction. However, according to the test results, especailly SWAT-3 Run 17, this type of failure cannot occur without wastage in the Monju operating conditions. Though the magnifying factor of hole diameters in the toroidal type would be the largest, the occurrence possibility of this type appears to be very small. The hole itself is the largest in the burst type.

As for the effect of the condition inside tubes (water or gas) on the magnitude of the failure, failure sizes in the gas-filled tubes are larger than those of the water-filled tubes. All failures larger than one DEG occurred in gas-filled tubes.

5.3 Extent of Damaged Area

The extent of the damaged area depends on the duration of injection, the water leak rate, etc., but in general more than about thirty tubes should suffer wastage and many of them are bowing or bulging in cases such that the leak rate exceeded 1 kg/sec.

Fig. 5.3 shows the extent of the damage in Run 10 where the water was injected from Tube 29 for 54 seconds at the leak rate of 570 g/sec. Tubes 47, 38 and 46 failed, and there were thirty tubes whose wall thinned more than 0.1 mm, surrounded by dotted lines in this figure. Arrows represent directions and degrees of the tube bowing. It appears that the directions of bowing are from the secondary leak sites to the outer area of the tube bundle as a whole.

Bulging was observed in most of the gas-filled tubes. It could be explained the result of high temperature, typically above 1000 °C, shown in Fig. 5.4. However, as the bulging was not observed in Run 14 where all tubes were filled with water, it seems to depend significantly on the heat transfer coefficient of the inside and outside wall.

6.0 DEVELOPMENT OF LEAP CODE

6.1 Outline of the LEAP Code

As described above, it is thought that failures by overheating without wastage would not occur in the Monju operating conditions. Therefore, the tube failure caused by wastage was mainly considered. Computer code LEAP (Leak Enlargement and Propagation) was developed to predict the failure propagation by wastage.

It can simulate the failure propagation processes from the occurrence of initial water leak, to the leak detection, to the water dump, and to the termination of the reaction, and simultaneously to calculate the maximum leak size due to the failure propagation.

A flow diagram of the failure propagation phenomena is outlined in Fig. 6.1. Analytical modeling of individual processes are listed below.

1) Calculation of the water leak rate
   To calculate the water leak rate from each hole on the tube.

2) Decision on wastage points
To specify the wastage points considering the shapes of the flame jets and the interference effect between jets.

3) Target wastage
To calculate the wastage rate for each wastage point on the tubes considering the water leak rate, distance between the hole and tube, etc., by using empirical formulas derived from the experimental studies at PNC.

4) Penetration of the target tube
To calculate the time required for the tube failure and the hole-size enlargement by using empirical formula.

5) Self-enlargement of the leak nozzle
To calculate the time of enlargement and the enlarged size.

6) Leak detection time
To calculate the detection time by the leak detector such as the hydrogen meters.

7) Pressure build-up in cover gas region
To calculate the pressure build-up in the cover gas region, considering the amount of hydrogen generated from the reaction and released through the gas line in order to determine the detection time of the pressure transducer in the cover gas and the rupture disc burst signal.

8) Time mesh control
To select the best time mesh to minimize the calculation time.

Besides, what should be provided as preconditions are as follows:

9) Initial leak data
Position, direction, and diameter of the initial leak nozzle.

10) Tube data
Size, material and configuration of the tube.

11) Steam generator condition
Water/steam conditions at initial stage and during water dump.

These elements are linked one another in the LEAP code as shown in Fig. 5.4.

6.2 Comparison with SWAT-3 Test Data

Runs 14 and 15 in SWAT-3 are the full-sequence simulation tests, that is, all of fifty-six tubes were filled with the water at 150 ata(15 MPa), and the water injection was stopped after the decrease of the water supply tank pressure which simulated the water dump under a sodium-water reaction accident in the actual steam generator system.

Comparisons between the time history of the Run 14 test result and that of LEAP calculation is shown in Fig. 6.3. As shown clearly, the calculation always provides a conservative value for both the time and the size of the failures. The maximum water leak rates of the test result and the calculation are 900 and 2900 g/sec, respectively.

From the comparison above, it is concluded that though the present LEAP code can not exactly identify the failed tube and the jet direction after a few stages of propagation, it can conservatively predict the total leak size and the timings of individual tube failures for the analysis of the actual plant. The results of the analyses are described in the paper presented by T. Takahashi, Y. Ohmori and Y. Hoshi.1)

7.0 CONCLUSION

The following conclusions can be drawn from the SWAT-1 and SWAT-3 failure propagation tests and analyses.

1. Wastage was the dominant mechanism which caused the failure propagation. There seems to be no failure by overheating without wastage under the Monju operating conditons.
2. The magnifying factor of the penetration of the gas-filled tube was larger than that of the water-filled tube.
3. The total water leak rates were far less than that of one DEG even in the full-sequence simulation tests including the water dump.
4. More than thirty tubes suffered wastage in the case that the water leak rate exceeded 1 kg/sec. And bowing and bulging were also observed in these tubes.
5. The wastage damage due to water leak into cover gas space is slight.
6. The LEAP code can conservatively predict the total leak size taking accont of failure propagation.

- REFERENCE -

1. T. Takahashi, Y. Ohmori, and Y. Hoshi, "Influence of Sodium-Water Reaction on Monju Steam Generator," Japanese Paper in the IAEA/IWGFR Specialists' Meeting, the Hague, Nov., 1983.

Table 3.1 Summary of Conditions and Results of SWAT-1 Propagation Tests

Run No.		82	83	84	92	94	4101	4102	4103	4104	4105	4106	4107	4108	4109	4110	4111	4112	4113
Sodium Temp.	°C	397	395	389	411	410	329	400	394	399	399	400	401	390	383	382	385	$\frac{345}{366}$	356
Water Heater Temp.	°C	300	300	320	310	331	300	332	326	330	333	326	330	311	311	215	315	$\frac{319}{310}$	317
Water Heater Pressure	ata	127	125	128	128	129	126	130	120	127	132	120	125	122	120	158	126	$\frac{145}{130}$	154
Leak Nozzle Diameter	mm	2.5	1.5	1.2	1.5	2.5	3.0	0.8	0.8	1.2	1.8	2.0	1.8	1.8	1.2	0.7	1.2	$\frac{2.0}{3.0}$	3.0
Water Leak Rate	g/sec	119	61.7	32.9	58.1	119	194	9.59	9.47	28.5	76.2	75.1	66.2	46.8	26.8	37.5	25.7	$\frac{111}{100}$	139
Failure Time	sec	(44.8)	(54.9)	71.6	45.4	55.2	48.2	57.2	181	67.4	52.7	52.5	75.0	72	85	—	89	$\frac{-}{-}$	—
Wastage Rate	$\times 10^{-2}$ mm/sec	6.63	5.41	4.15	6.54	5.38	5.54	5.19	1.64	4.41	5.64	5.69	4.48	4.64	3.49	—	4.25	$\frac{-}{-}$	—
Failure Size	mm × mm	-	-	17.4 × 20.0	3.4×9.1 2.4×4.3	8.0 × 1.7	5.5 × 0.7	5.2 × 9.4	3.8 × 4.0	-	-	2.9 × 4.4		6.7 x 5.4	4 x14 4 x15	—	4 x12 3 x14	$\frac{-}{-}$	—
L / D	-	25	42	52	10	25	21	29	31	52	9.9	4.4	66.7	66.7	52	61.7	51.7	$\frac{27.4}{17.7}$	20.7
Collision Angle	deg	0	0	0	0	45	90	45	90	90	45	0	0	0	0	0	0	$\frac{0}{0}$	0

Table 4.1 Main Specifications of SWAT-3 Heat Transfer Tubes

Run No.		8	9	10	11	12	13	14	15	16	17
Tube Material		$2\frac{1}{4}$Cr-1Mo Steel									
Tube Size [mm]		25.4mm OD 3.2mm thickness			31.8mm OD 3.8mm thickness					31.8mm OD 3.13mm thickness	
Tube Number	Total	100	100	100	55	52	56	56	56	92	93
	Initial Leak Tube	1	1	1	1	1	1	1	1	1	1
	Water Tube	2	2	0	2	6	1	55	55	6	4
	Gas Tube	25	25	24	9	9	13	0	0	50	60
	Dummy Tube	72	72	75	43	36	41	0	0	35	28

Table 4.2 Summary of Conditions in SWAT-3 Failure Propagation Tests

Run No.	8	9	10	11	12	13	14	15	16	17
Test Date	8/9/79			5/22/80			9/30/80	4/1/81	9/28/81	5/27/82
Reaction Vessel	Evaporator									
Tube Size mm	25.4mm OD 3.2mm thickness			31.8mm OD 3.8mm thickness					31.8mm OD 3.13mm thickness	31.8mm OD 3.13mm thickness
Tube Material	$2\frac{1}{4}$Cr-1Mo Steel									
Initial Leak Site mm	FL4403	FL5403	FL3330	FL5403	FL4371	FL3366	FL4403	FL4415	FL4143	FL4128
Initial Leak Dia. mm	0.8	0.25	4.0	0.3	1.5	6.0	0.5	0.3	10	5
Initial Leak Rate g/sec	36	6.8	570	- *	87	920	18	14	2200	1460
Pres. in WH ata	149	149	152	152	150	151	149	158	153	153
Temp. in WH °C	341	341	343	342	342	343	240	346	340	250
Sodium Temp.	343	358	400	336	334	372	341	335	340	320
Sodium Flow	Stagnant									
Termination of Injection	after 3rd Fail.	after 3rd Fail.	after 2nd Fail.	after 3rd Fail.	after 3rd Fail.	until 100kg of water injected	after Blow Down	after Blow Down	60 sec	60 sec

* Injection system malfunctioned

Run No.		8	9	10	12	13	14	15	16	17
Initial Leak Nozzle Dia. mm		0.8	0.25	4.0	1.5	6.0	0.5	0.3	10	5
Water Heater Pressure ata		149	149	152	150	151	149	158	153	153
Water Heater Temperature °C		341	341	343	342	343	240	346	340	250
Failure Propagation	1st Leak Rate g/s Time sec	36 0	6.8 0	570 0	87 0	920 0	18 0	14 0	2200 0	1460 0
	2nd Leak Rate g/s Time sec	170 55	No Propagation for 36 min.	(N_2 gas) 50	260 74	(N_2 gas) 70	210 94	62 50	4500 24	—
	3rd Leak Rate g/s Time sec	(N_2 gas) 125			1,350 147	≀ several gas tubes failed ≀	470 145	95 195	*	—
	4th Leak Rate g/s Time sec	1,500 155		—	—		810 168	1,020 224		—
	5th Leak Rate g/s Time sec	—				1,000 158	900 215	2,740 253		—
Injection Time sec		160	2180	54	152	168	293	311	60	60
Injected Water kg		27	14	32	39	125	110	132	228	81
Number of Damaged Tubes	Failed Tubes	3	0	3	4	9	4	4	25	0
	Bowing Tubes (≥1.0mm)	above 30	0	17	13	14	9	30	61	21
	Buldging Tubes	3	0	17	2	about 20	*few*	*few*	33 (>1.0mm)	18 (>1.0mm)
	Thinned Tubes (≥0.1mm)	about 40	3	about 30	18	25	9 (>1.0mm)	17 (>1.0mm)	6 ** (>1.0mm)	3 (>1.0mm)

Table 4.3

SWAT-3 Test Results

*24 Gas Tube failed from 12sec to 48sec after initiation of water injection because the inner pressure increased 185 to 213 ata.

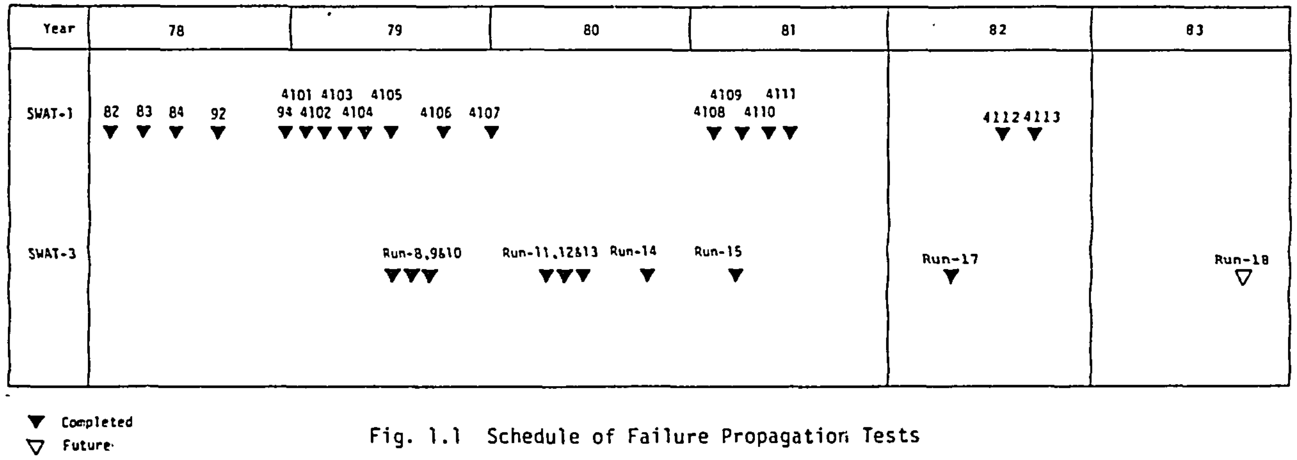

Fig. 1.1 Schedule of Failure Propagation Tests

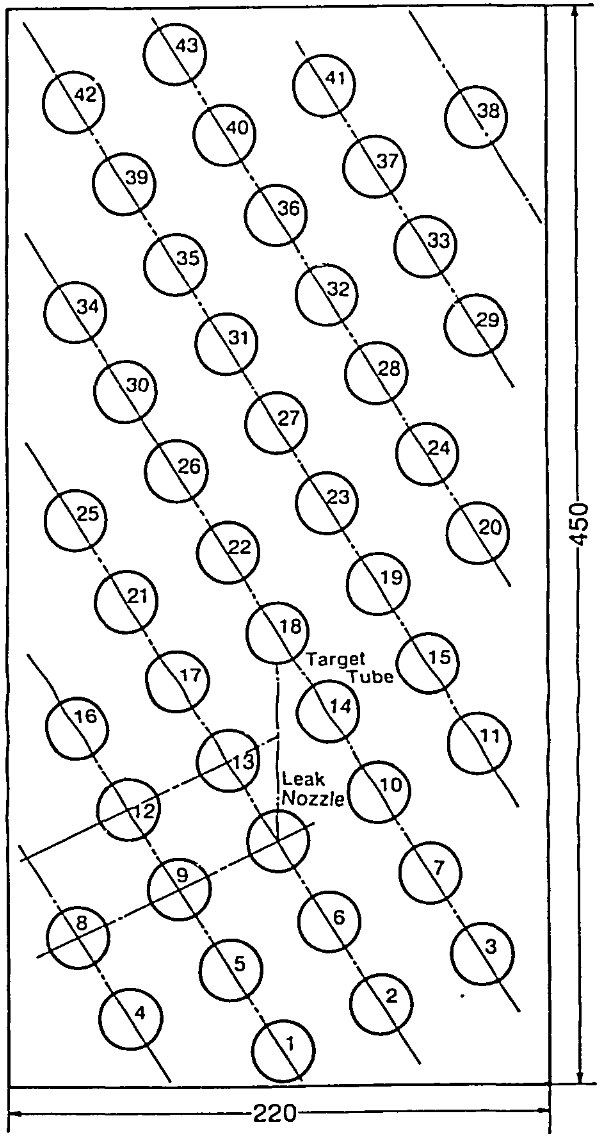

Fig. 3-1 SWT-1 Tube Bundle Configuration

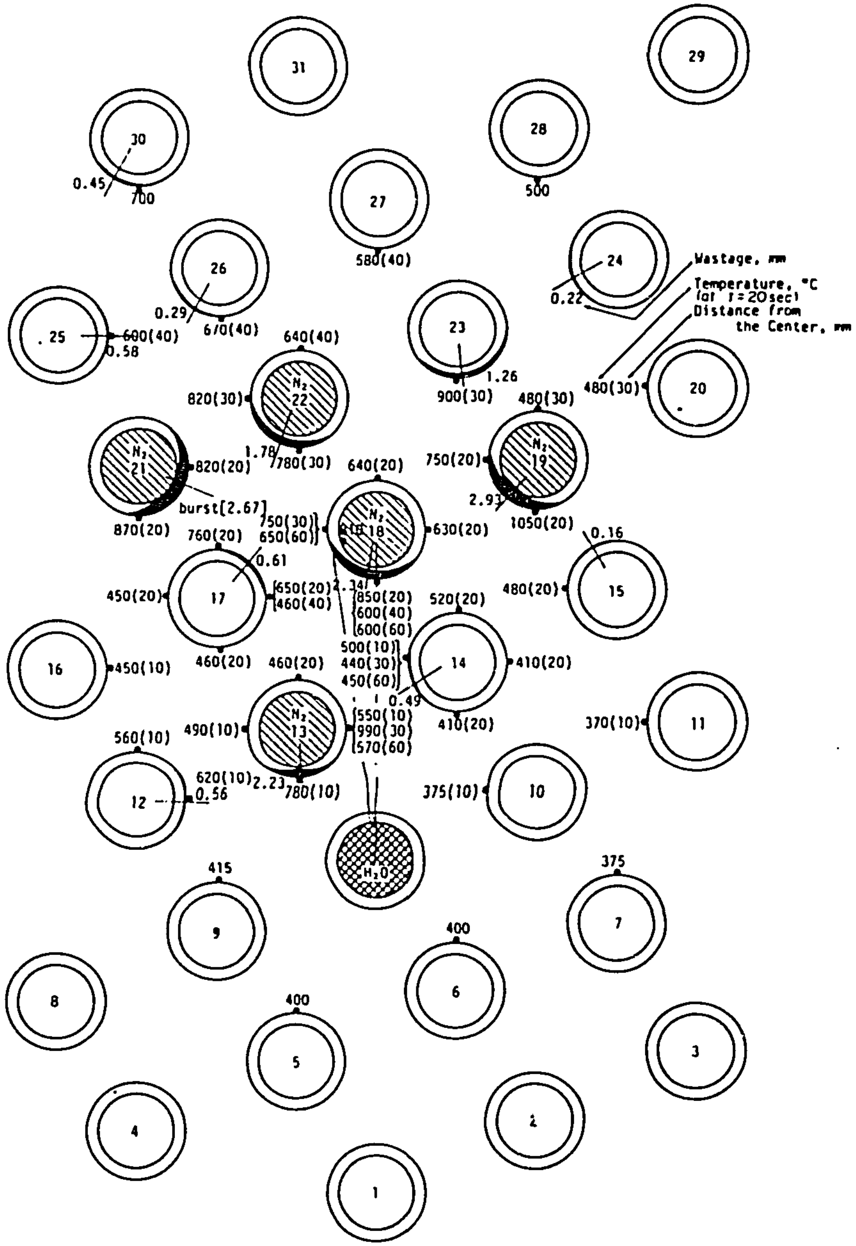

Fig. 3.2 Multiple Wastage of Tubes and Reaction Temperature in Run 4101

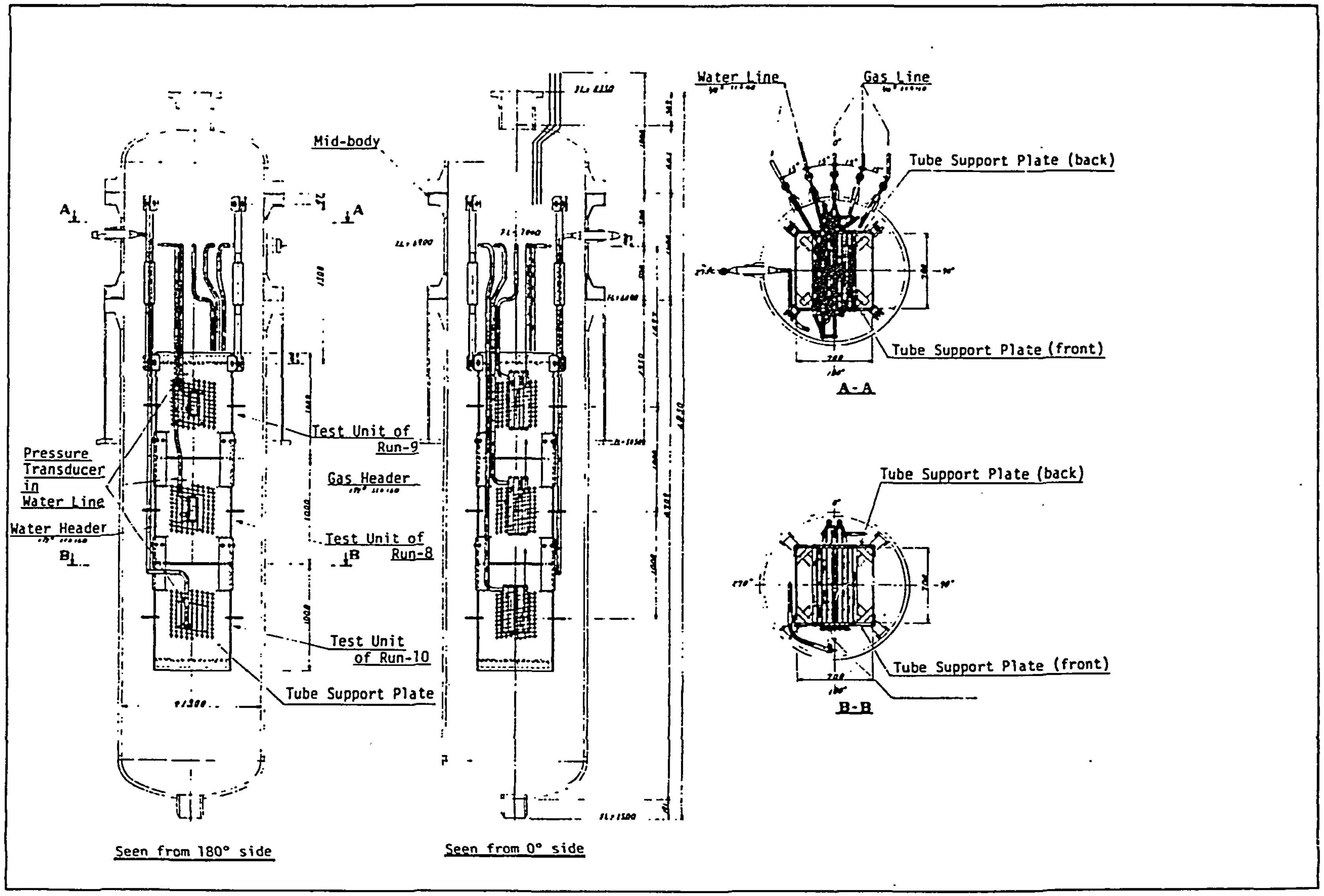

Fig. 4.1 Configuration of Internals in SWAT-3 (Run-8, 9 and 10)

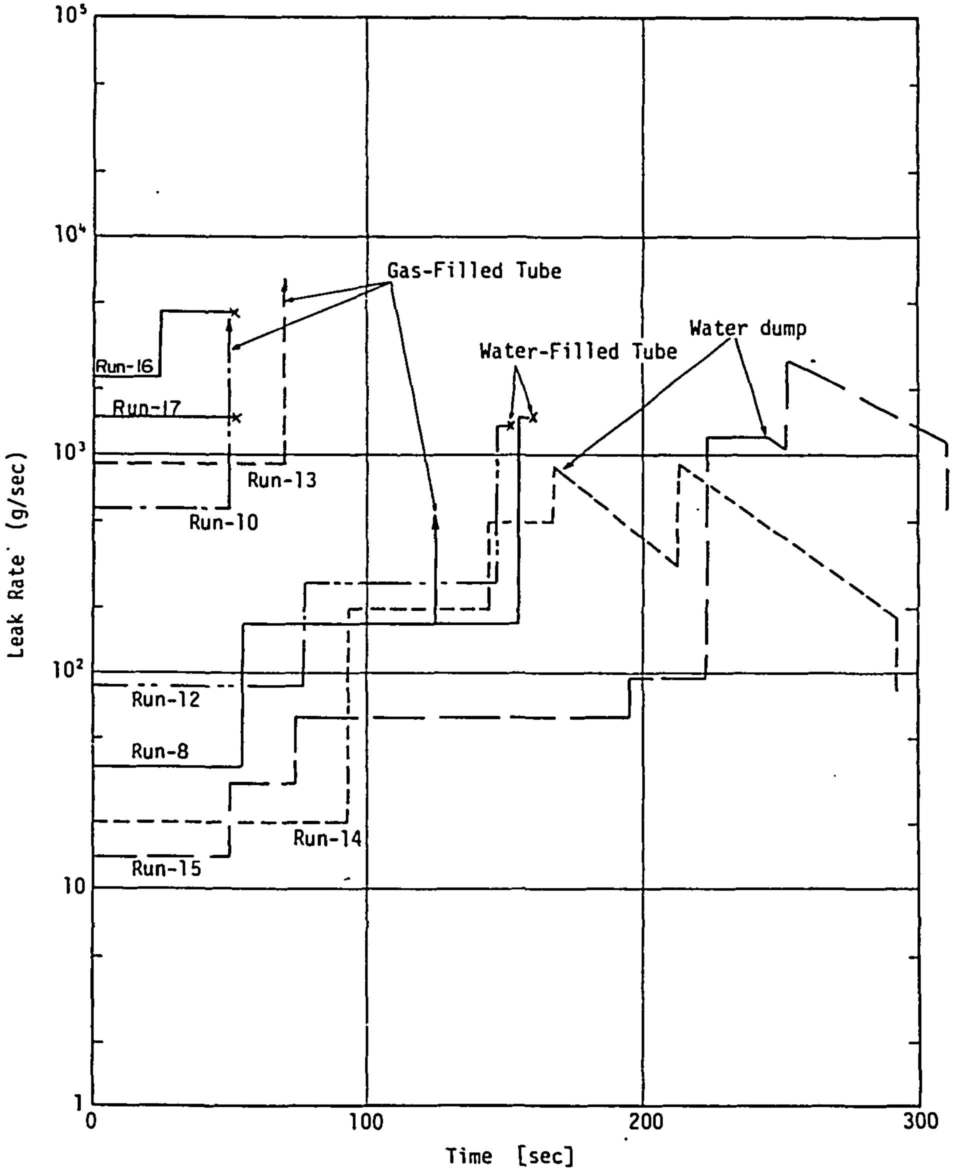

Fig. 4.2 Time Sequence of Water Leak Rate in SWAT-3 Tests

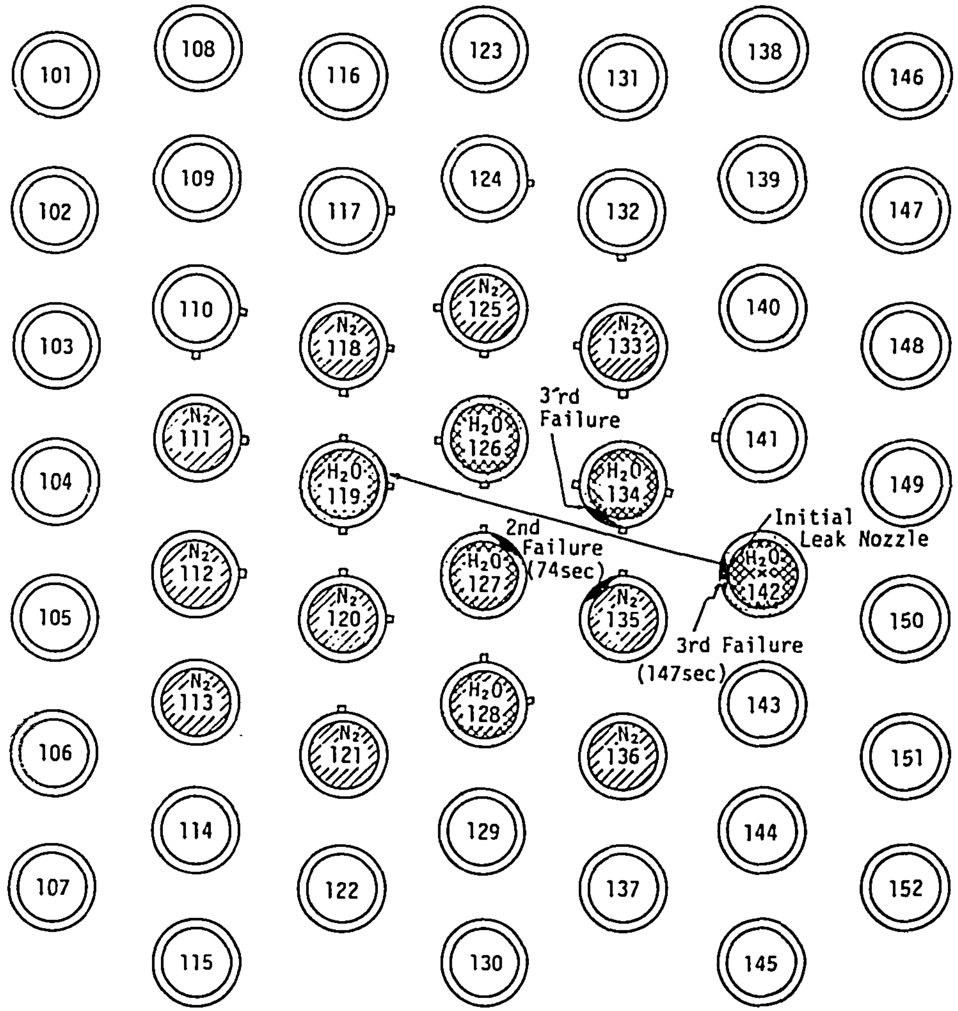

Fig. 4.3 Failure Propagation Profile in SWAT-3 Run-12

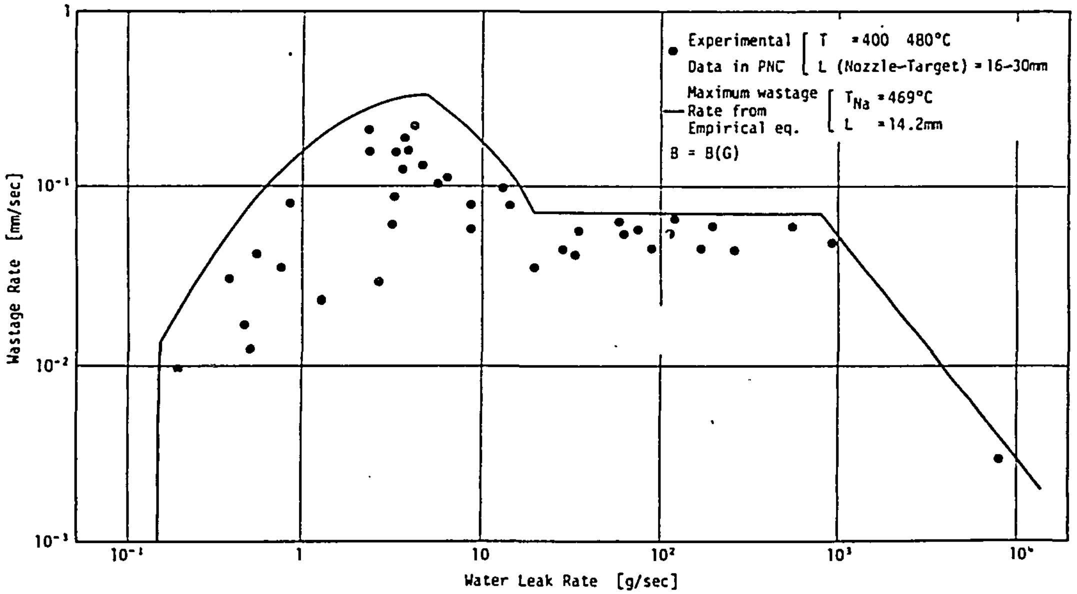

Fig. 5.1 Relation between Water Leak Rate and Wastage Rate

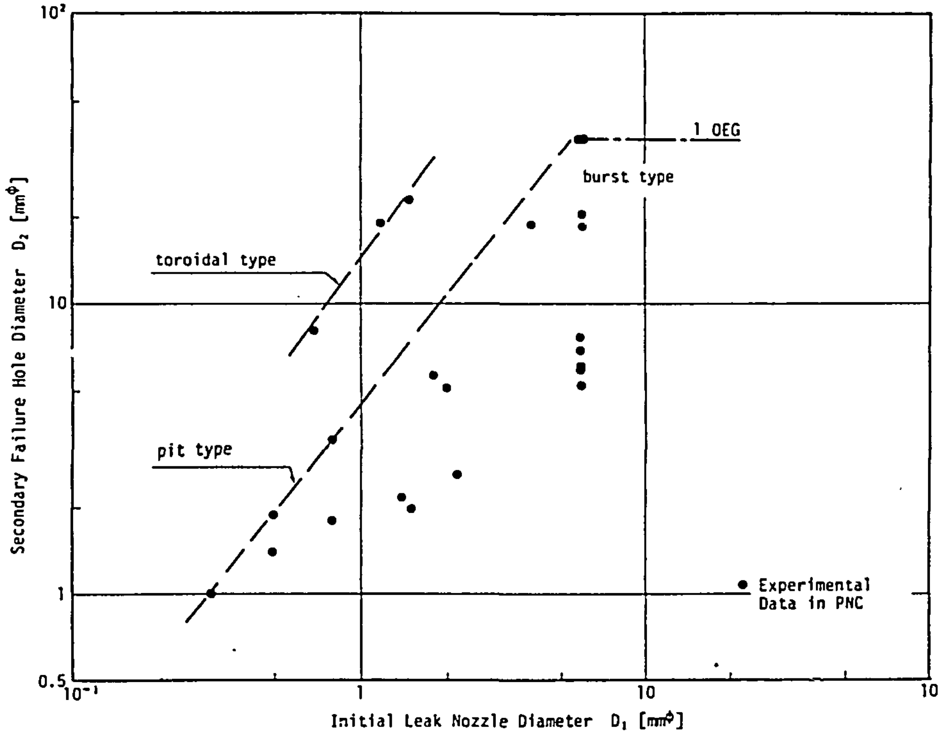

Fig. 5.2 Relation between Initial Leak Diameter and Secondary Failure Diameter

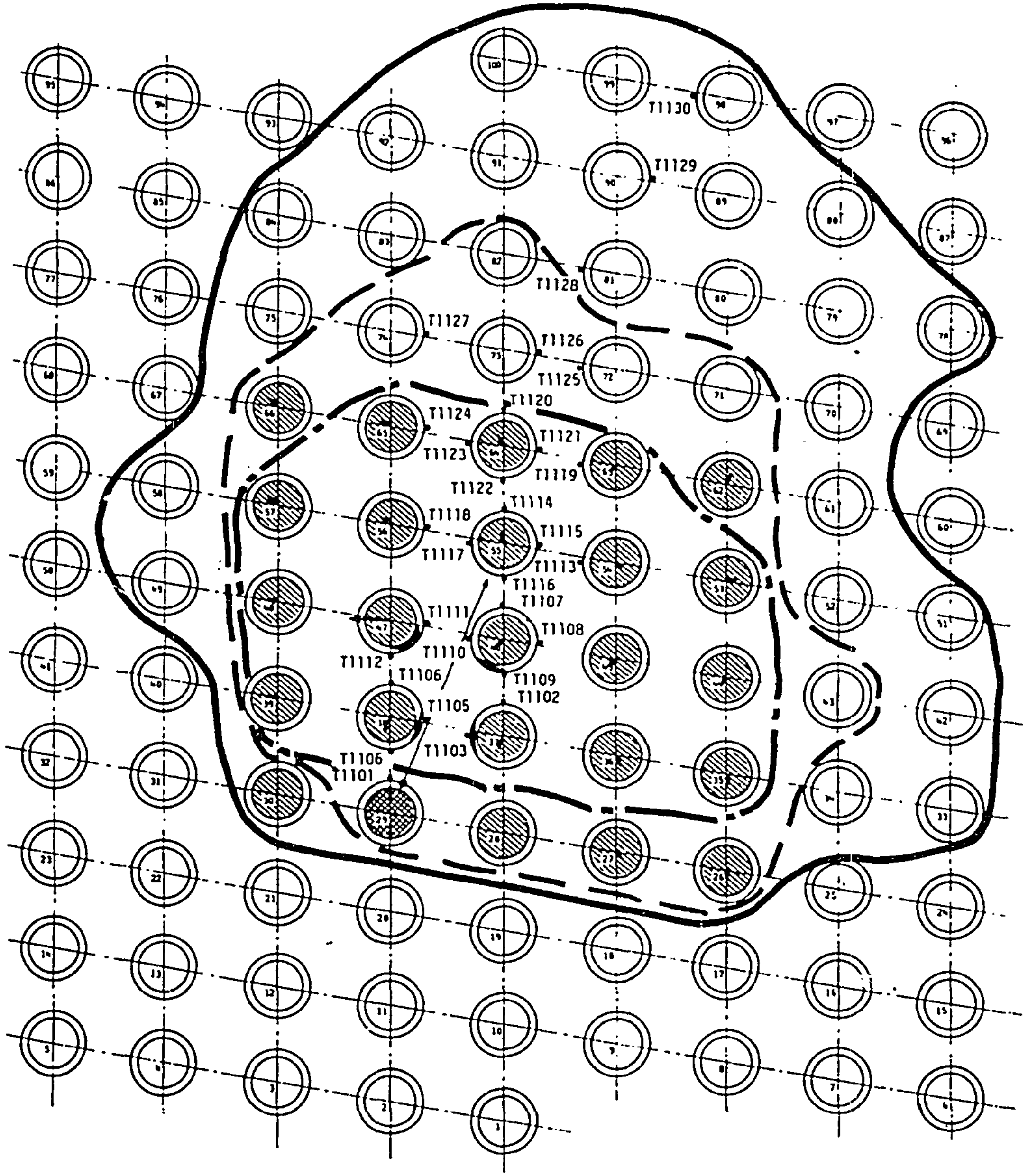

Fig. 5.3 Tube Damages Produced by SWAT-3 Run-10 Test

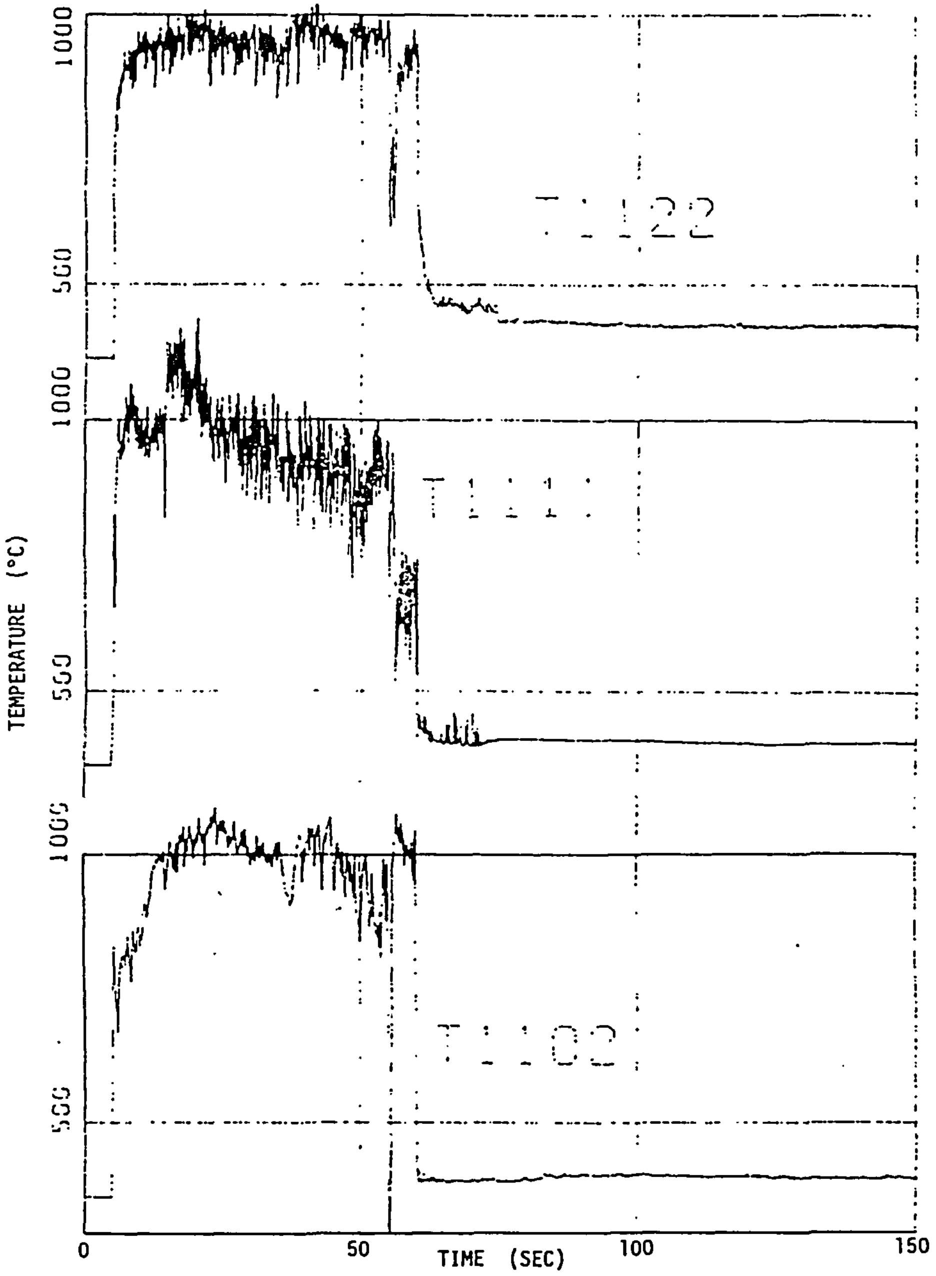

Fig. 5.4 Typical Temperature Traces in the Reaction Zone in Run-10

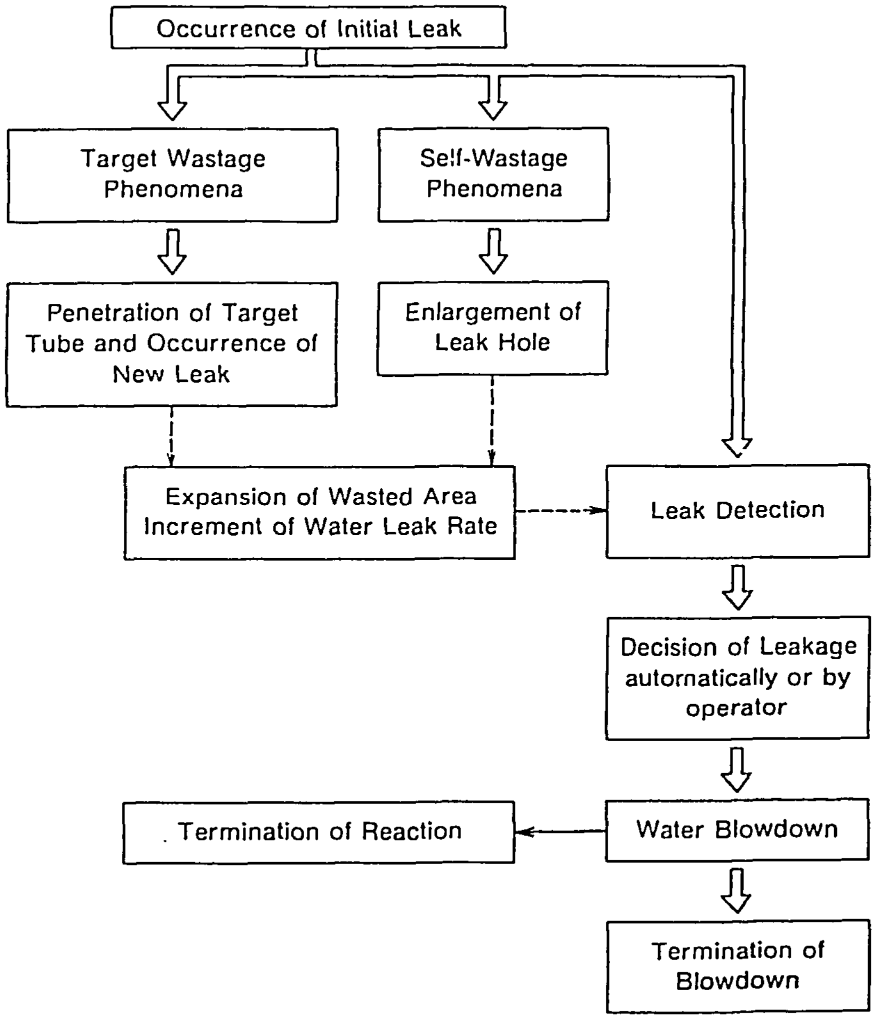

Fig. 6.1 Modeling of Steam Generator Failure Propation Phenomena

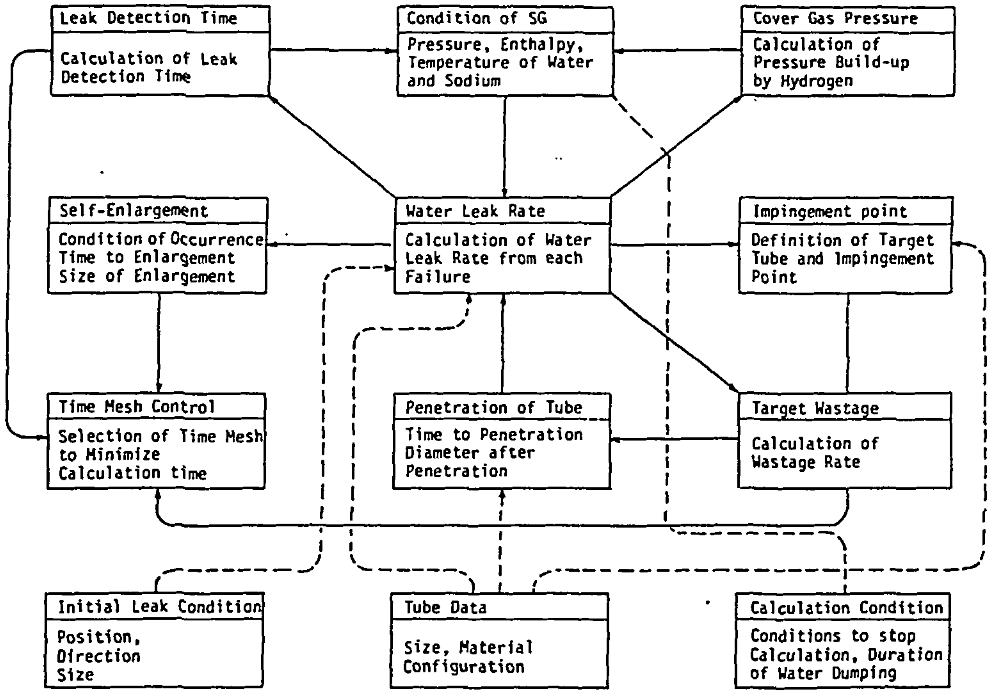

Fig. 6.2 Link of LEAP's elements

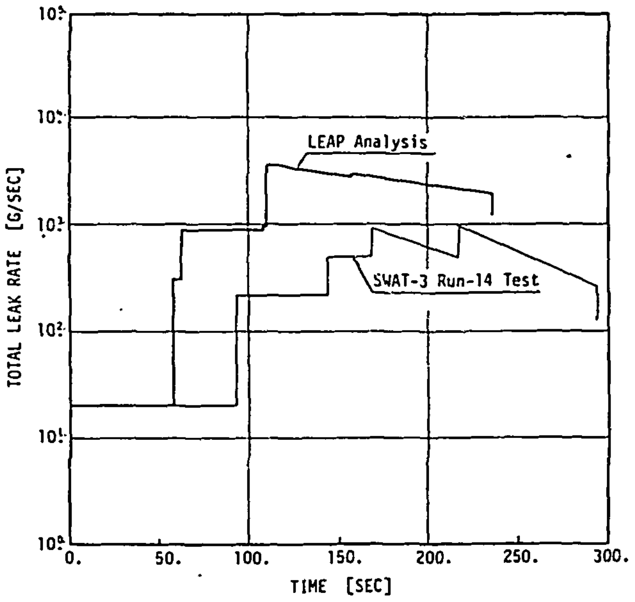

Fig. 6.3 Comparison between the Run-14 Test Result and LEAP Analysis