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EXPERIMENTAL STUDIES ON LEAK PROPAGATION OF HEAT TRANSFER TUBES BY SWAT-1 AND SWAT-3

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EXPERIMENTAL STUDIES ON LEAK PROPAGATION OF HEAT TRANSFER TUBES BY SWAT-1 AND SWAT-3

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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. The 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 steam generators that have suffered leaks.

Initially eleven fundamental tests were performed in a intermediate leak region using the SWAT-1 test rig, and then seven failure propagation tests were 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 a full term simulation test, including a water dump was far less than that of one double-ended-guillotine (DEG) failure. A further test program is to be conducted so as to provide a much more explicit simulation of the MONJU design.

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1. INTRODUCTION

It is considered necessary to perform near-prototypical sodium-water reaction proof tests in order to select a design basis leak (DBL) for the LMFBR MONJU steam generators and to establish the operational method for responding to sodium-water reaction accidents.

In PNC seven large leak sodium-water reaction tests were conducted using the Steam Generator Safety Test Facility (SWAT-3). In these tests no failure propagation occurred and damage to adjacent tubes was slight.[1)-6)] In the small leak region fundamental tests were executed to obtain data such as the wastage rate using the Small Leak Sodium-Water Reaction Test Loop (SWAT-2).[7)-9)] It seemed that data in a intermediate leak region were lacking for completing the whole story of failure propagation phenomena where the water leak rate would increase step by step from a small leak to a large leak.

In the first stage of the failure propagation tests, eleven tests were performed using the Large Leak Sodium-Water Reaction Test Rig (SWAT-1) with the purpose of gathering the wastage data in the intermediate leak region.[10)] Mainly learned was how the wastage rate and the magnitude of the secondary failures were affected by some parameters. The water leak rate was in the region of 10 g/sec - 200 g/sec. Target tubes were filled with nitrogen gas pressurized up to 140 ata (14 MPa).

There were some problems or limitations in using the SWAT-1 test rig. That is, as the diameter of the SWAT-1 reaction vessel is about 1/6 of that of the MONJU evaporators, for a large water leak rate the potential for secondary failures from stationary flame front effects might be underestimated. Another problem was that the temperature increase due to the reaction heat was considered to limit the total amount of water to be injected in the SWAT-1 reaction vessel.

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.[11)] The diameter of the SWAT-3 evaporator is about half 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. Main target tubes were filled with water or nitrogen gas pressurized up to 150 ata (15 MPa). Seven tests have been conducted so far examining the effects of the parameters such as the initial leak rate and the direction of the leak jet. Fig. 1 shows the failure propagation test schedule of the SWAT-1 and the SWAT-3 tests.

2. 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 history of the failure propagations.
2. Provide data to select the DBL.
3. Define the potential for tube failures due to the overheating.
4. Provide data on re-use of tubes in the failed steam ganerators.

3. 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 shown in Fig. 2 contained about thirty tubes of 25.4 mm OD with a nominal wall thickness of 3.2 mm and a length of 240 mm, and was suspended in the reaction vessel. The material of the tubes was $2\frac{1}{4}$Cr-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. A pressure of 140 ata (14 MPa) of nitrogen was applied to the inside of several main target tubes so as to simulate the tube bursting. Others tubes had both ends open.

More than fifty thermocouples were distributed around the tubes for the measurement of the reaction temperature. They were placed apart from the axial center so as not to prevent the tube wastage. 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 the auto-measuring and plotting system and metallurgical examinations were also conducted.

3.2 Test Conditions

The conditions of the eleven tests are outlined in Table 1. To achieve the objectives descrived 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, and D means the leak nozzle diameter. L/D was chosen from the region 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 region of 0 - 90 deg.

The following parameters were fixed through the tests:

1. Water/steam condition - the saturation pressure around 120 ata (12 MPa).
2. Sodium conditions - stagnant, the temperature around 400°C (exept Run-4101).
3. Tube arrangement - chosen according to the MONJU design.

3.3 Test Results

Fig. 3 shows the status of tube damages in Run-4101 in order to explain the 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 No.18. Tube No.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

No.21 after the disassembly of the internals.

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 penetration holes obtained for the gas tubes is 19 mm.
4. A dominant mechanism of the secondary failures is not overheating but wastage.

4. SWAT-3 TESTS

4.1 Test Facility

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

1) Internals

Internals of Run-8 through 10 are shown in Fig. 4. In Run-11 through Run-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 Run-8 through 10. In Run-14 the internals consisted of a single test unit because the water injection line is complicated as descrived later.

2) Tube

Main specifications of the tubes are indicated in Table 2. All of these failure propagation tests in SWAT-3 simulate the conditions of the evaporators, therefore $2\frac{1}{4}$Cr-1Mo steel is chosen as the material of tubes. At first tubes of 25.4 mm OD with a nominal wall thickness of 3.2 mm were used as in the SWAT-1 tests, but after Run-11 tubes of 31.8 mm OD with a nominal wall thickness of 3.8 mm have been used according to the unification of specifications of the MONJU steam generators.

Hence the total number of tubes in a test decreased after Run-11. Four types of tubes are used in the SWAT-3 tests as follows:

Initial leak tube	:	After opening of the injection valve, a piston inside this tube moves to open the flow area to the sodium side due to the high pressure of water.
Water tube	:	These water tubes are connected to the same header as the initial leak tube. After the progress of failure propagation they would become the second or third leaking tubes.
Gas tube	:	Gas tubes surround the two types of tubes mentioned above and are filled with nitrogen gas pressurized up to 150 ata (15 MPa).
Dummy tube	:	Dummy tubes surround other types of tubes. They have both ends open.

All of these tubes are straight so that the state of wastage can be measured easily and precisely. Though all tubes in Run-14 were filled with water, in other tests few tubes were the water tubes. The reason is as follows: at an early stage we had been afraid that the water leak rate might exceed the allowed value of the SWAT-3 test facility due to the failure propagations, but after Run-13 we were sure of the integrity of the SWAT-3 facility with the help of a interlocking circuit with signals of the water leak rate and the total amount of injected water.

3) Water injection line

In Run-8 through 13 the water injection line was modified so that up to 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 both the initial leak tube and the other water-filled tubes inside the evaporator. But since in Run-14 all tubes were designed to be filled with water in order to provide a better simulation of the MONJU steam generators, the water injection line became more complicated especially inside the evaporator. Hence, Run-14 was carried out with a single water injection line.

4) Instrumentation

In order to obtain how the failure propagation might progress, measurements as below are prepared:

Thermocouple	:	Thirty thermocouples were placed to measure the temperature around tubes.
Turbine flowmeter	:	To measure the water leak rate.
Pressure transducer	:	To measure the pressures at the time of secondary failures.
Acoustic detector	:	Accelerometer type, to trace the failure propagation.

4.2 Test Conditions

Test conditions of the failure propagations in SWAT-3 are summarised in Table 3. The minimum value of the initial water leak rates was 6.8 g/sec in Run-9, and the maximum value was 920 g/sec in Run-13. The water in the supply tank was saturated in Run-8 through 13 and subcooled in Run-14, but the pressures were about 150 ata (15 MPa) in all tests.

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

Run-8 - 10 : As they were the first sequential failure propagation tests, the initial leak rates were selected from wide range, that is, intermediate, small and relatively large leak rate for Run-8 through 10, respectively. That of Run-10 was expected to cover the lacking area which the series of SWAT-1 tests could not fill because of some limitations. As the secondary failure of Run-10 was expected to become too large, target tubes were not filled with water but with nitrogen gas.

Run-11 - 13 : According to the unification of specifications of the MONJU steam generators, tubes were changed to larger ones. The initial leak rates of Run-11 through 13 were in the region of small, intermediate, and large leak, respectively. Besides, searching for the possibility of high temperature yielding of tubes was one of the important objects in Run-13.

Run-14 : In accordance with the operational conditions of the MONJU steam generators during sodium-water reaction accidents, Run-14 was carried out to simulate the failure propagation phenomena from the beginning of the initial leak to the end of water dump from the water supply tank. In order to simulate the pressure decrease easily, the water in the supply tank was chosen to be subcooled and pressurized by 150 ata of argon gas, and all of 56 tubes were filled with water from the same supply tank.

Decisions as to when to stop the water injection were different in the objectives of each test in Run-8 through 14. For example, injection valves were closed right after a third failure had occurred in Run-8 and Run-12, but they were closed after a second failure in Run-10 and Run-13. Some measurements described in the previous paragraph were monitored in the control room to determine the propagation of the failures and to know when to close the injection valve.

4.3 Test Results

The results of SWAT-3 failure propagation tests are summarized in Table 4. Those of Run-11 were deleted from the table since water could not be injected on account of a malfunction of the injection system. In Run-9 no secondary failure occurred at least during 36 minites of the injection.

In Run-10 and 13, whose leak rates were relatively large, the water injection was stopped after the occurrence of a second failure, and in Run-8 and 12, the valves were closed after that of a third failure. In Run-14 at least four propagations were observed, and one failure occurred during blowing down of the water supply tank.

Results of Run-12 should be discussed as the typical case of propagation phenomena. The tube configuration is shown in Fig. 5. The injection was initiated from the leak nozzle of 1.5 mm diameter which would simulate the failure propagations from the intermediate leak region. Tube No.142 is the initial leak tube whose nozzle was directed nearly to tube No.119.

A second failure occurred on tube No.127 at 74 seconds after the injection. A third failure occurred on tube No.142 at 155 seconds.

The resulting water leak rate increased step by step, that is, from 87 g/sec to 260 sec, and to 1,350 g/sec. Besides these tubes No.134 failed, though the penetration hole was so small that the occurrence time of the failure could not be decided. A gas tube, No.135, also failed at 134 seconds. Photographs of failed tubes in Run-12 are shown in Fig. 6.

5. DISCUSSION

The results of failure propagation tests in SWAT-1 and SWAT-3 described in chapters 3 and 4 are discussed in more detail below.

5.1 Progress of Failure Propagations

The time histories of the water leak rate in SWAT-3 tests are shown in Fig. 7. Roughly speaking, it can be said that about one minute is necessary for each failure propagation and the leak rate of 10 - 50 g/sec as the initial value develops more than 1 kg/sec in a few minutes by propagations.

The failure times of Run-8 and 10, where relatively small tubes were used are shorter than those of Run 12 through 14 which used larger tubes. In consideration of the difference of tube wall thickness, the wastege rates are compared in Fig. 8 which indicates that the wastage rate of SWAT-3 not only exceeds the conservative equation derived from the data of SWAT-1 at low L/D, but also attenuates rapidly as the L/D value increases. The reason for this attenuation is that reflection and scattering of water by tubes at the larger SWAT-3 leak rates disturb the similarities between SWAT-1 and SWAT-3.

It appeares that there is no significant difference in the failure time between water and gas tubes.

5.2 Size of Penetration Hole

Generally speaking, a failure propagation tends to magnify the new penetration hole in comparison with the precursor hole. For the purpose of examining this tendency, the relation between equivalent diameters of second failures and initial nozzle diameters (or between third and second) are plotted in Fig. 9.

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 tubes are exposed to a relatively large leak jet, the wall thins in a wide area, and the tube splits in the axial direction. But there was no case that the burst type of failure occurred without wastage. Though the magnifying factor of hole diameters in the toroidal type would be largest, the occurring possibility of this type appears to be very small. The hole itself is largest in the butst type.

The effect of the condition inside tubes (water or gas) on the magnitude of the failure has not been concluded yet on account of insufficiency of the number of data. According to the data obtained so far, failure size in gas tubes is larger than that of water tubes. All of the failures larger than one DEG occurred in gas 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 were wasted and some other tubes were bowing or bulging in cases such that the leak rate exceeded 1 kg/sec.

Fig. 10 shows the extent of the damage in Run-10 when the water was injected from tube No.29 for 54 seconds at the leak rate of 570 g/sec. Tubes No.47, 38 and 46 failed, and there were thirty tubes whose wall thinned more than 0.1 mm, as 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 tubes. It could be explained to be the result of high temperature, typically above 1000 °C, shown in Fig. 11. However as the bulging was not observed in Run-14 when all tubes were filled with water, it seems to depend significantly on the heat transfer coefficient of the inside and outside wall.

6. SUMMARY

The Japanese test program on the failure propagation in LMFBR steam generators has been developing data for the selection of the design basis leak (DBL) and the establishment of the operational procedures for the sodium-water reaction accidents in the MONJU steam generators. The results of failure propagation tests in SWAT-1 and SWAT-3 are summarized as follows:

1. Wastage was the dominant mechanism which caused the failure propagation. There was no failure by overheating without wastage.
2. It took more than one minutes to penetrate the tubes of 31.8 mm OD.
3. The magnifying factor of the penetration hole of the gas tube was larger than that of the water tube.
4. The maximum size of the failures was 6 mm in diameter in case of the water tube, though the opening areas of a few gas tubes were equivalent to one DEG.
5. The total water leak rate was far less than that of one DEG even in the full term simulation test including the water dump.
6. About thirty tubes were damaged by the wastage when the water leak rate exceeded 1 kg/sec. And bowing and bulging were observed, mainly in some gas tubes.

Some correlations derived from these tests are applied in the LEAP code which analizes the failure propagation phenomena. All test programs have not been finished completely and some other tests are planned to provide the data of the remaining subjects as indicated below:

○ Propagation tests in a region of 1.5 kg/sec - 6.7 kg/sec which have not been performed so far.
○ Confirmation tests whether tube failures occur due to overheating under more near-prototypical conditions.
○ Tests under the superheater conditions.

These tests are to be performed using SWAT-1 initially and if necessary they will be confirmed in SWAT-3.

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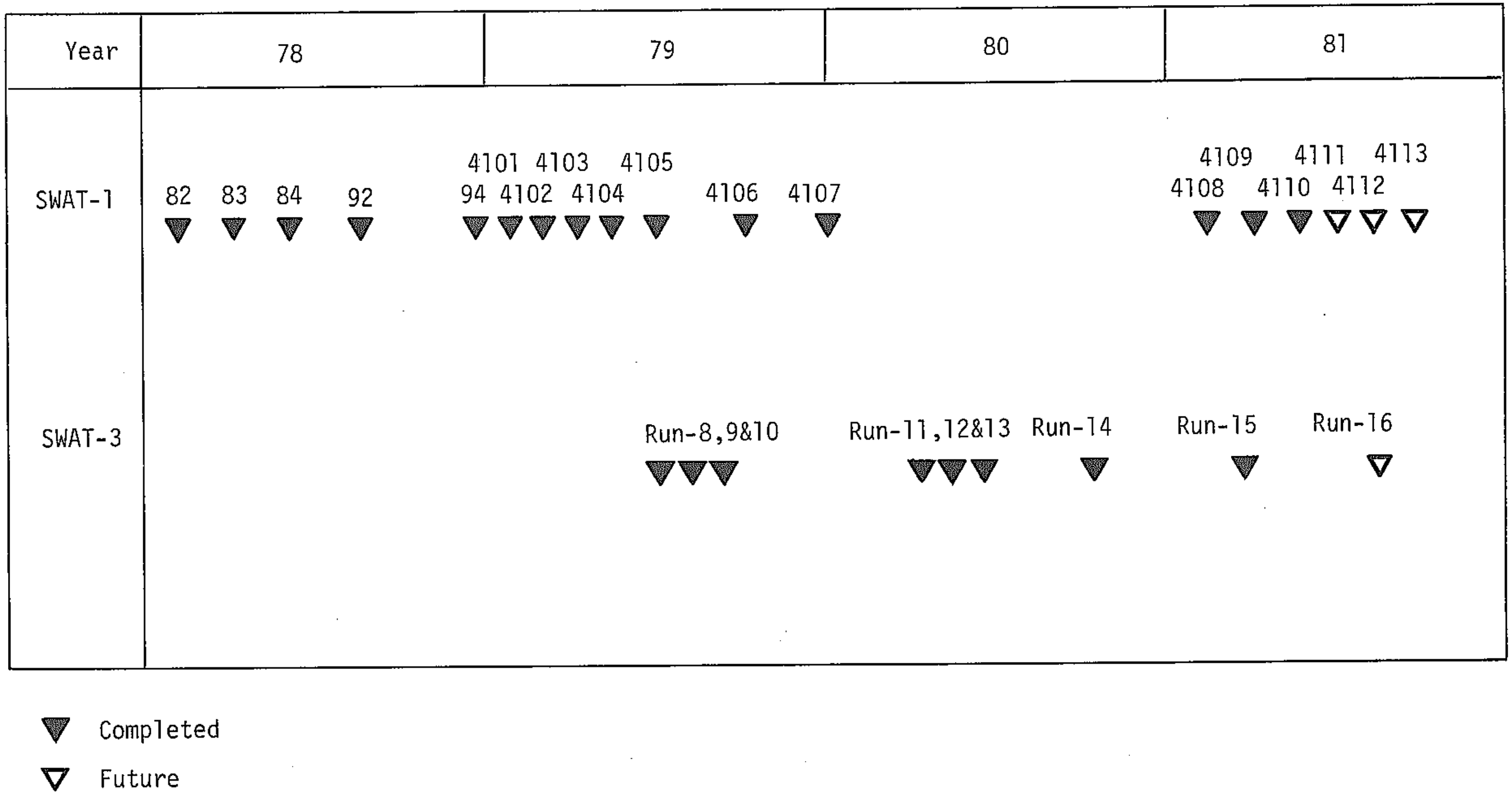


Fig. 1 Schedule of Failure Propagation Tests

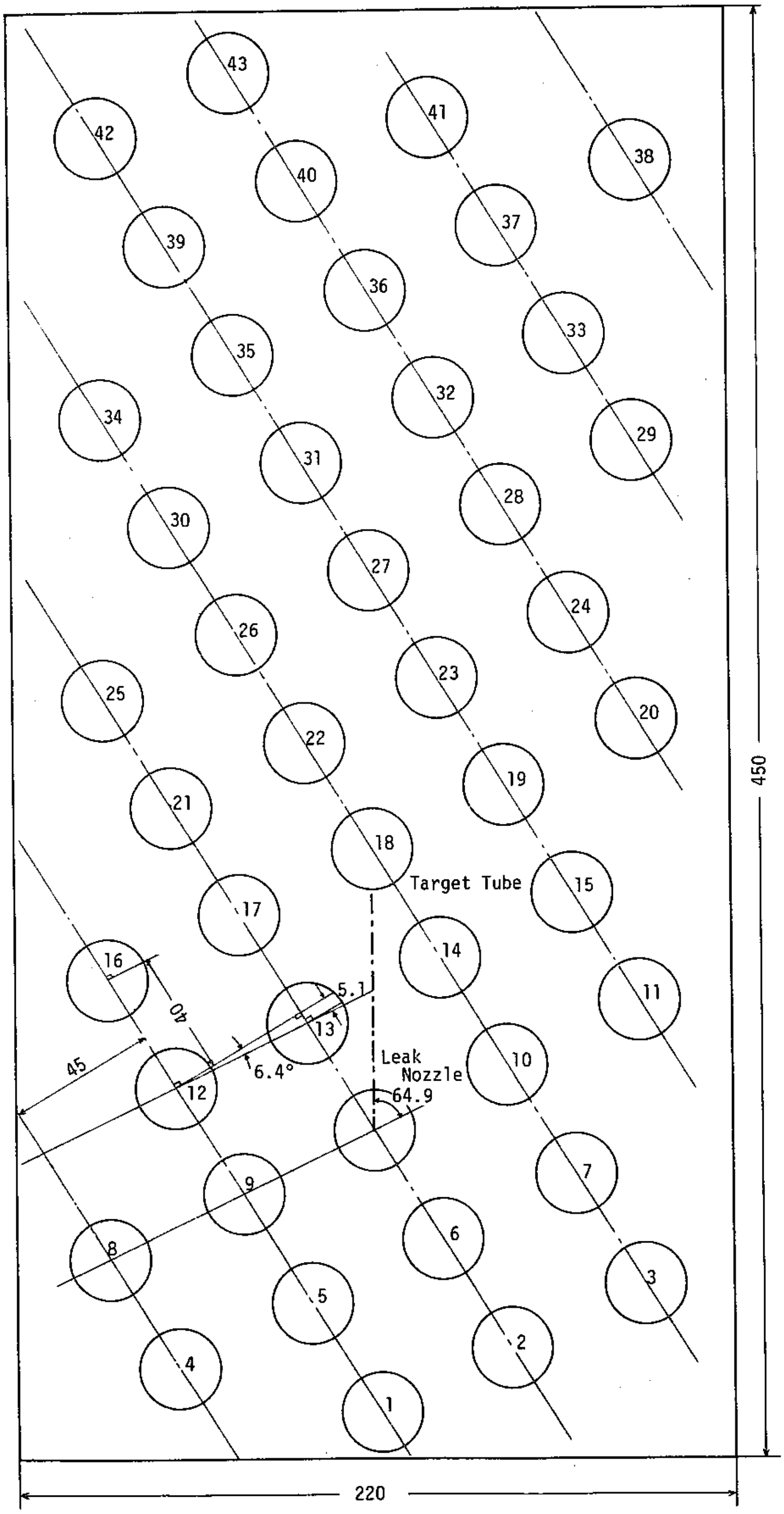


Fig. 2 SWAT-1 Tube Bundle Configuration

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

Run No.		82	83	84	92	94	4101	4102	4103	4104	4105	4106
Sodium Temp.	°C	397	395	389	411	410	329	400	394	399	399	400
Water Heater Temp.	°C	300	300	320	310	331	300	332	326	330	333	326
Water Heater Pressure	ata	127	125	128	128	129	126	130	120	127	132	120
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
Water Leak Rate	g/sec	119	61.7	32.9	58.1	119	194	9.59	9.47	28.9	76.2	75.1
Failure Time	sec	(44.8)	(54.9)	71.6	45.4	55.2	48.2	57.2	181	67.4	52.7	52.5
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
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
L / D	-	25	42	52	10	25	21	29	31	52	9.9	4.4
Collision Angle	deg	0	0	0	0	45	90	45	90	90	45	0

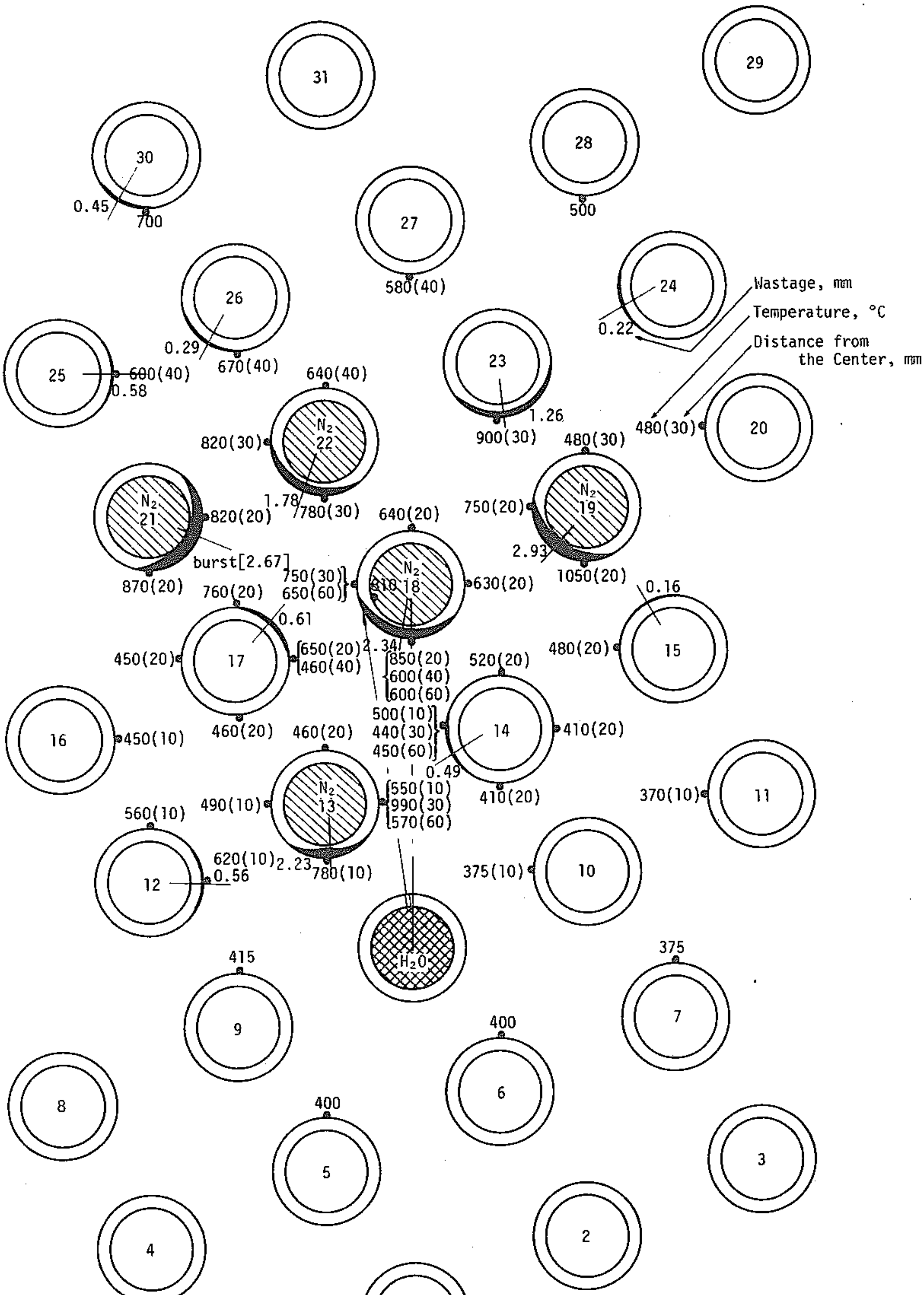
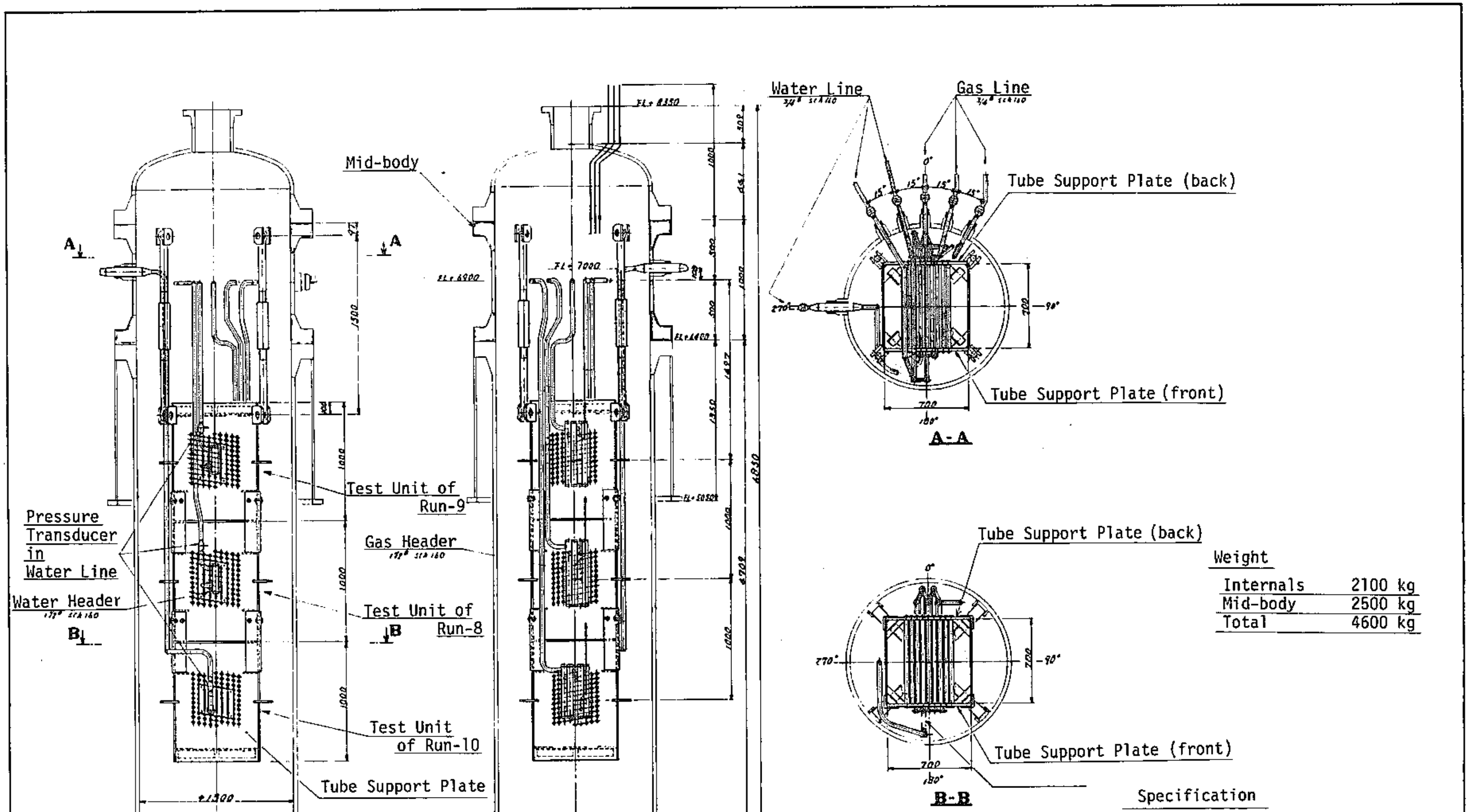


Fig. 3 Multiple Wastage of Tubes and Reaction Temperature at t = 20 sec in Run 4101



Specification

	Inside Gas Tube	Inside Water Tube	Outside Tube
Fluid	Nitrogen	Water	Sodium
Design Pressure	200 at	150 at	20 at
Design Temperature	550 °C	550 °C	535 °C
Testing Pressure	200 at	150 at	–

Fig. 4 Configuration of Internals

Table 2 Main Specifications of SWAT-3 Heat Transfer Tubes

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

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

Run No.	8	9	10	11	12	13	14
Test Date	8/9/79			5/22/80			9/30/80
Reaction Vessel	Evaporator						
Tube Size mm	25.4mm OD 3.2mm thickness			31.8mm OD 3.8mm thickness			
Tube Material	$2\frac{1}{4}$Cr-1Mo Steel						
Initial Leak Site mm	FL4403	FL5403	FL3330	FL5403	FL4371	FL3366	FL4403
Initial Leak Dia. mm	0.8	0.25	4.0	0.3	1.5	6.0	0.5
Initial Leak Rate g/sec	36	6.8	570	- *	170	920	20
Pres. in WH ata	149	149	152	152	153	153	149
Temp. in WH °C	341	341	343	342	343	343	240
Sodium Temp.	343	358	400	336	333	369	341
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

* Injection system malfunctioned

Table 4 SWAT-3 Test Results

Run No.			8	9	10	12	13	14
Initial Leak Nozzle Dia.		mm	0.8	0.25	4.0	1.5	6.0	0.5
Water Heater Pressure		ata	149	149	152	152	153	149
Water Heater Temperature		°C	341	341	343	342	343	241
Failure Propagation	1st Leak Rate	g/s	36	6.8	570	87	920	20
	1st Time	sec	0	0	0	0	0	0
	2nd Leak Rate	g/s	170	No Propagation for 36 min.	(N_2 gas)	260	(N_2 gas)	150
	2nd Time	sec	55		50	74	70	93
	3rd Leak Rate	g/s	(N_2 gas)		—	1,350	~ several gas tubes failed ~	500
	3rd Time	sec	125			147		145
	4th Leak Rate	g/s	1,500			—		1,600
	4th Time	sec	155					168
	5th Leak Rate	g/s	—				1,000	1,000
	5th Time	sec					156	220
Injection Time		sec	160	2180	54	153	168	293
Injected Water		kg	27	14	32	39	125	64
Number of Damaged Tubes	Failed Tubes		3	0	3	4	9	4
	Bowing Tubes		above 30	0	17	18	10	few
	Buldging Tubes		3	0	17	few	about 20	few
	Thinned Tubes		about 40	3	about 30	19	21	13

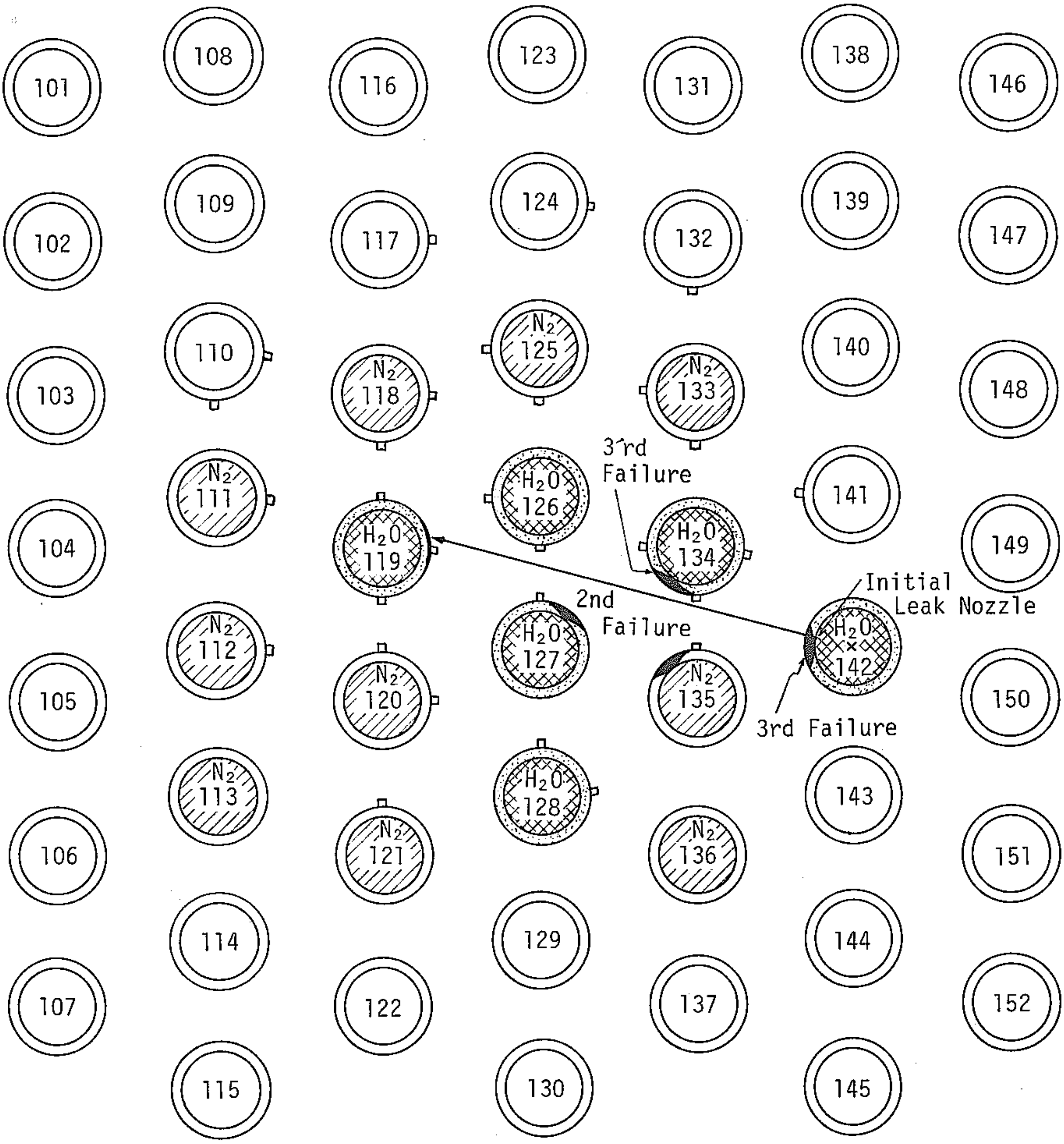


Fig. 5 Tube Configuration of SWAT-3 Run-12

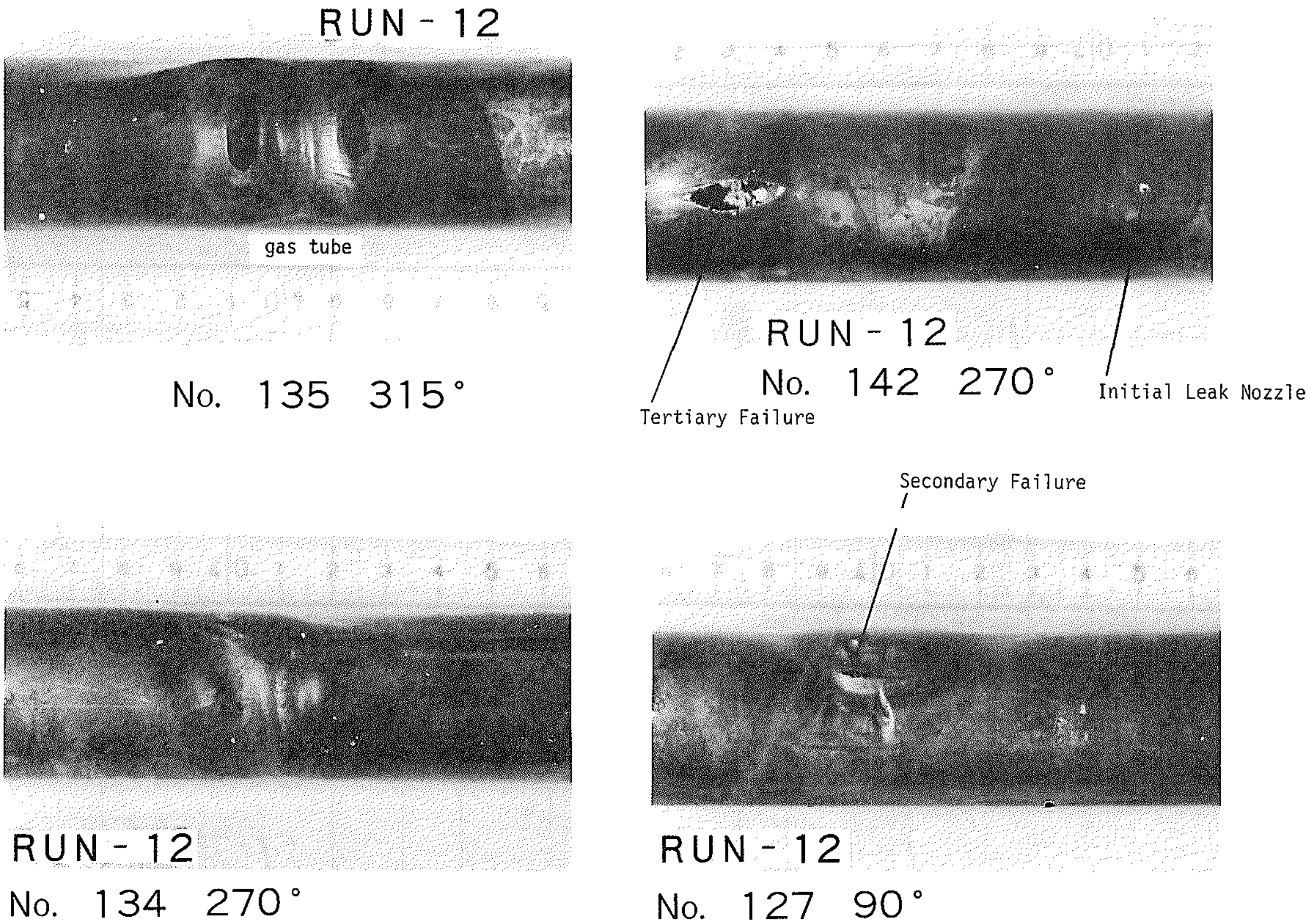


Fig. 6 Photographs of Failed Tube in SWAT-3 Run-12

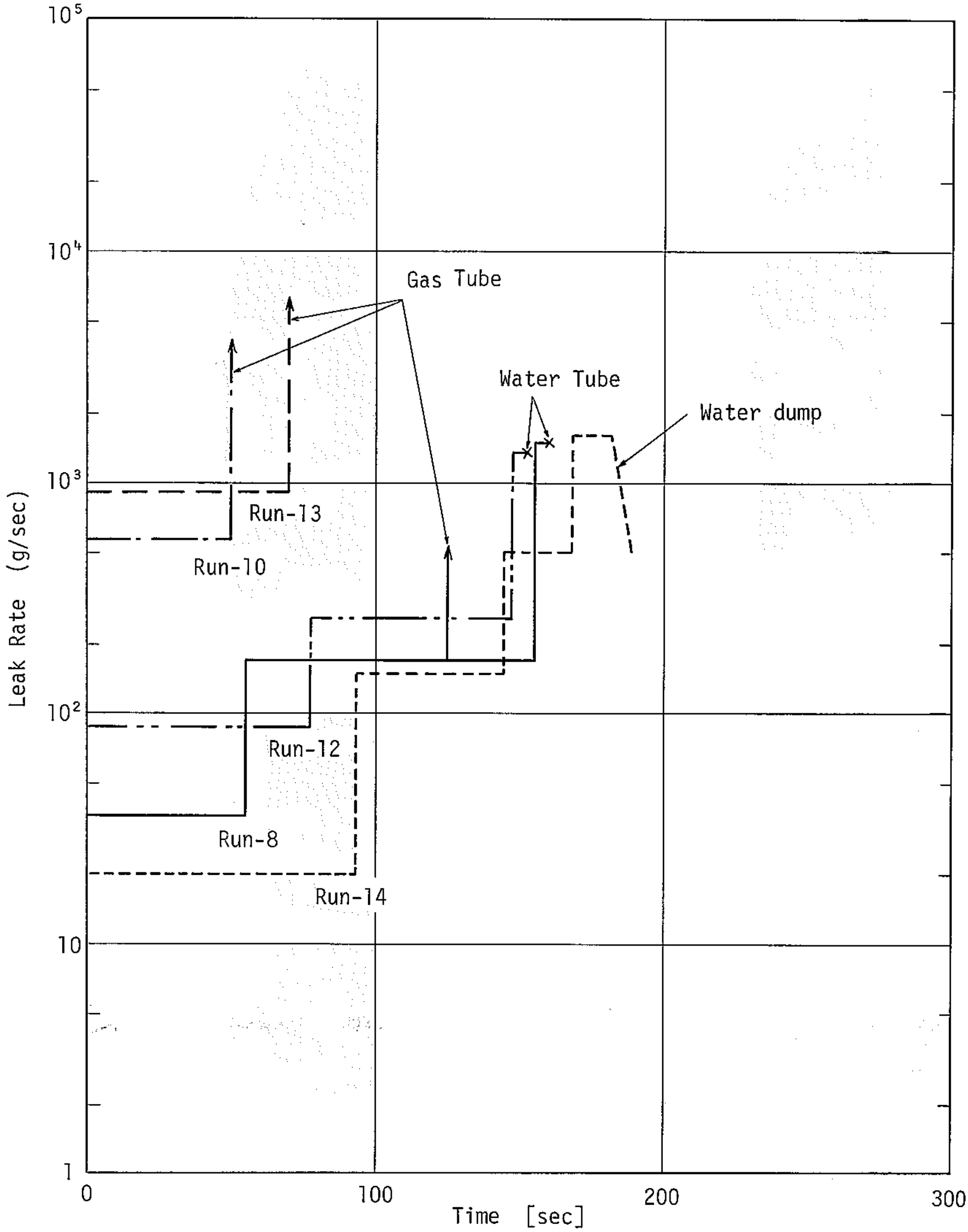


Fig. 7 Time Sequence of Water Leak Rate in SWAT-3 Tests

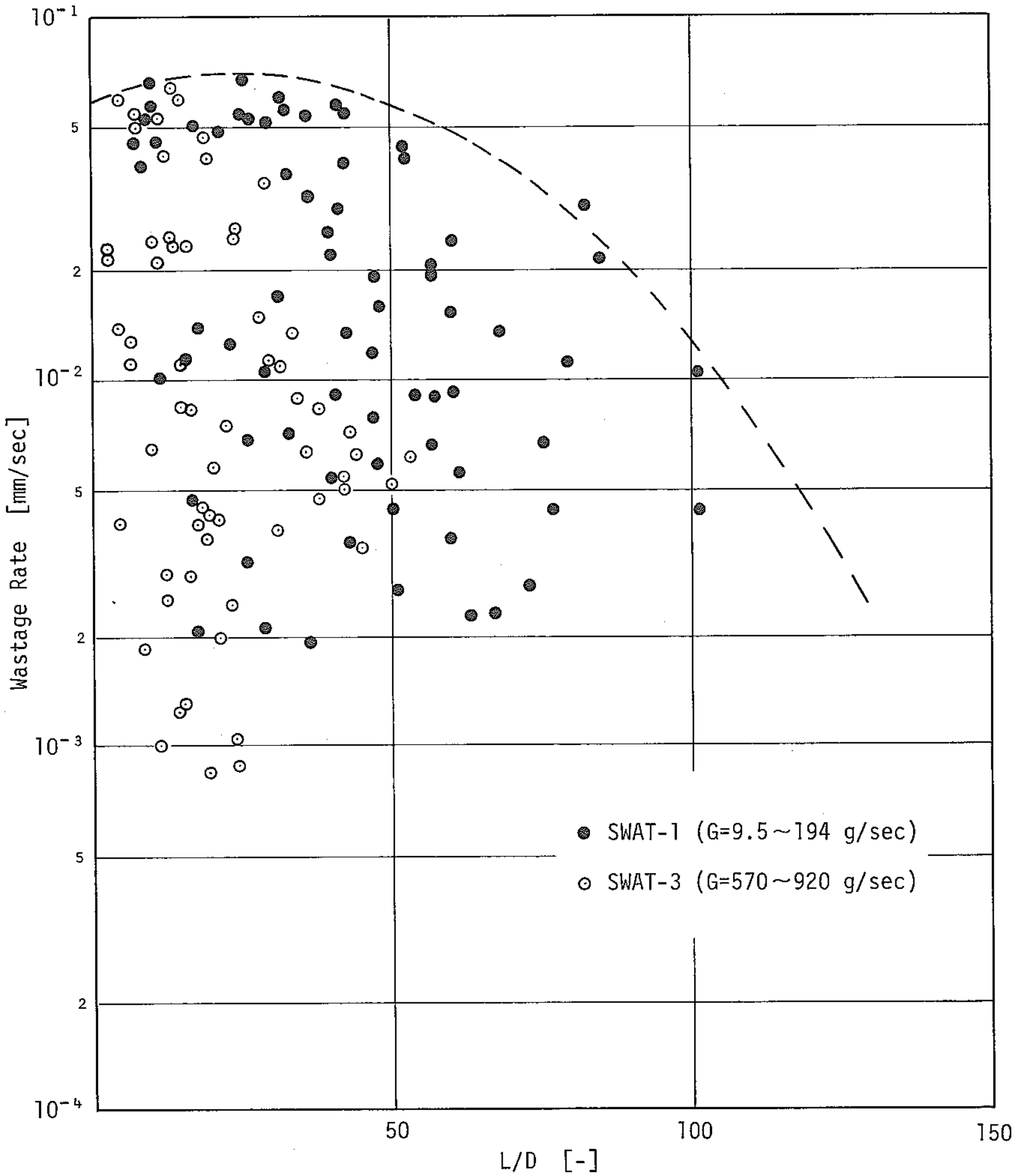


Fig. 8 Relation between Wastage Rate and L/D

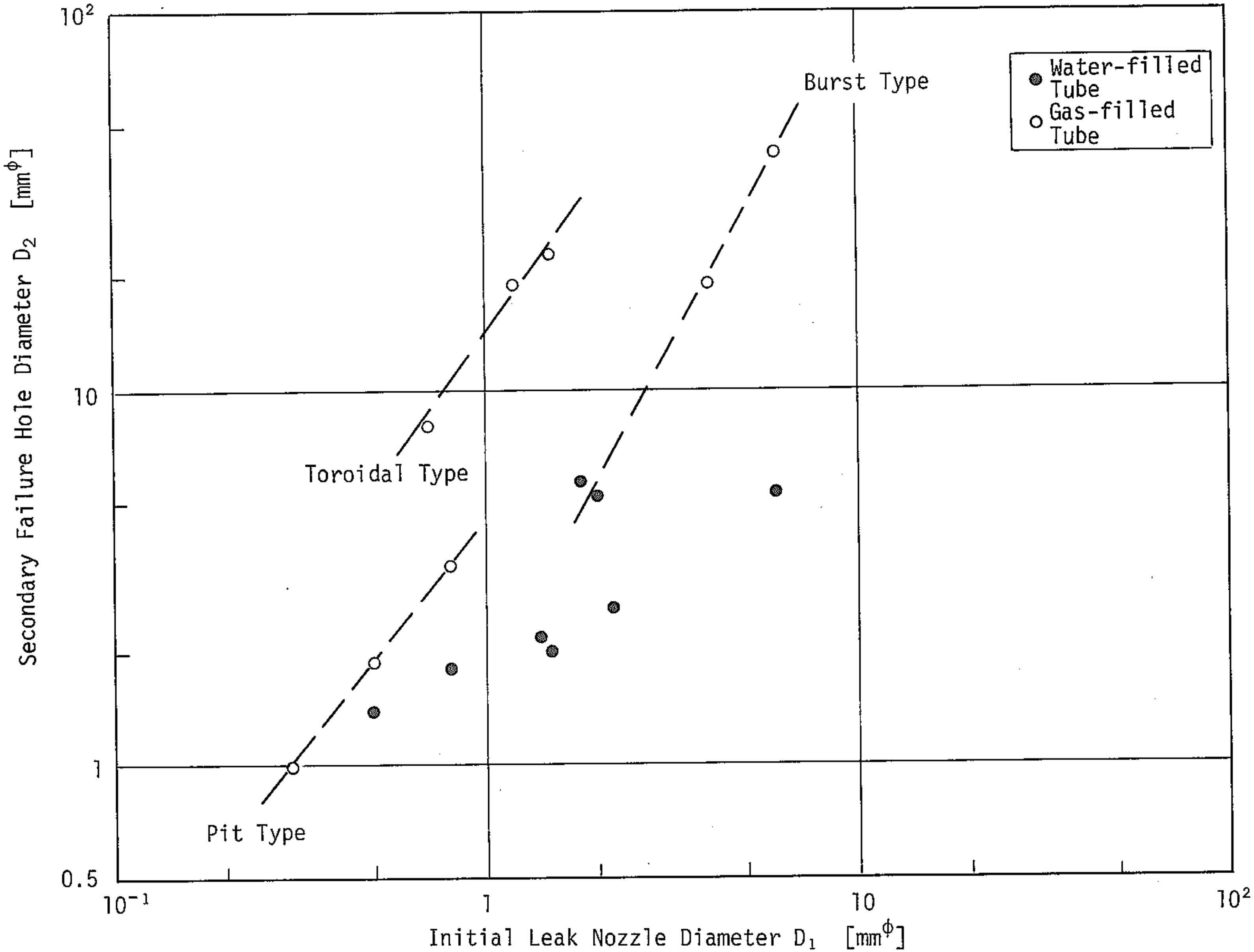


Fig. 9 Relation between Initial and Secondary Leak Diameter

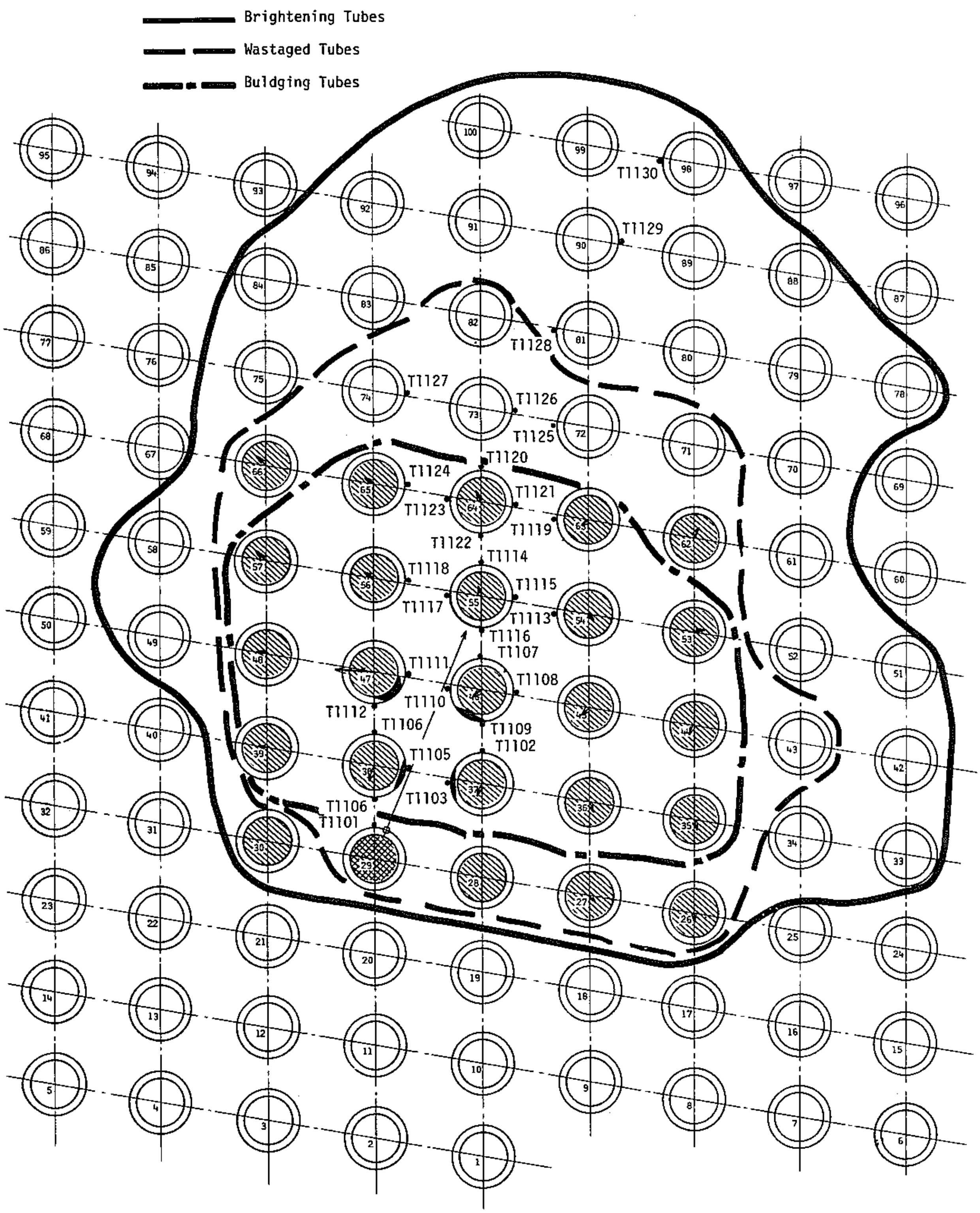


Fig. 10 Tube Damages Produced by SWAT-3 Run-10 Test

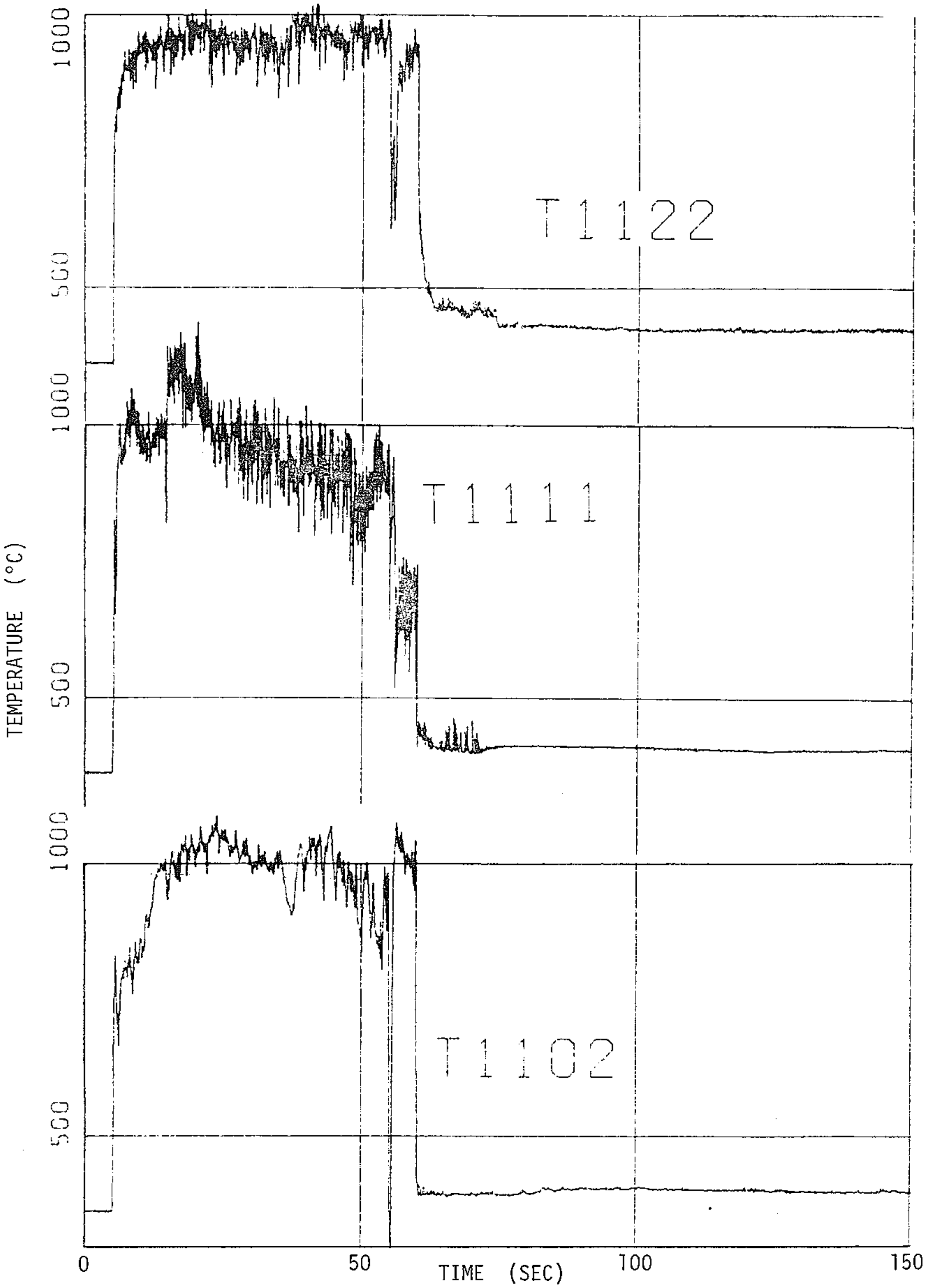


Fig. 11 Typical Temperature Traces in the Reaction Zone in Run-10