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MASTER

SELECTION OF TRANSITION LEAK SIZE FOR LLTR SERIES II TEST A-4

893/30/3-10

by

J. M. Roberts
L. M. Quintana

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GENERAL ELECTRIC COMPANY
Advanced Reactor Systems Department
Sunnyvale, California

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1.0 INTRODUCTION

Test A-4 in the Series II test program for the LLTR test rig is currently defined in the test request* as the size leak which is just large enough to generate local voiding (hydrogen plus steam) around the leak site, thus eliminating any jet-type stationary flames and adjacent tube wastage. This transition size leak is marginal with respect to keeping the bubble growing without breaking up into a series of small bubbles that allow the jet flame to become re-established by the return of sodium to the leak site.

To understand the rationale behind a transition leak one needs to consider the extremes of leak sizes. The leaks at the low end of the range, $\sim 10^{-4}$-10^{-2} lbs/sec, are known to form flame-type jets which reach out into the sodium distances which are roughly proportional to the leak size, assuming no obstructions are in the flame jet path. These flames remain stationary as long as the leak rate is held constant. Any obstructions placed in this flame will be heated, and like any flame, the amount of heating and wastage produced at the surface of the obstruction (in this case, another steam generator tube) depend on the position of the obstruction with respect to the flame. This results in wastage rates and patterns which are functions of the ratio leak size to target distance.

Leaks at the highest end of the scale are referred to as DEG or double-ended guillotines. A DEG leak is the maximum leak rate that a single tube can generate. It's generally accepted that a DEG does not produce a jet-type stationary flame because the amount of steam released and hydrogen formed create a large gas void and high pressure which bursts the rupture disc and rapidly expels the sodium from the vessel. This is sometimes referred to as piston-type evacuation of the vessel.

Decreasing leak sizes from the DEG with its large bubble voiding vs increasing leak sizes from the stationary flame jets produced by very small leaks leads one to wonder what leak size would produce a basic change or transition from a jet flame to a large growing bubble that voids a large volume in the vessel. Questions to be resolved include the nature of this transition, its stability, whether there is some type of intermediate phenomena which bridges the gap, the parameters

*Test Request given in Reference 12

influencing transition, how the transition size can be predetermined, and its reproducibility. The objective of this report is to provide the basis for the selection of this transition leak size for testing in the LLTR. This test, designated as Test A-4, is of particular interest because, of all the larger non-flame-jet-type leaks, it has the longest dwell time in the vessel before the rupture disc blows, thus terminating the IHTS pressure rise. Its potential for generating secondary leaks is considered high. It is easy to postulate the generation of such a leak starting with small leak wastage and progressing into larger and larger leak sizes by self-wastage and adjacent tube wastage. On the other hand, it is not easy to postulate an instantaneous DEG failure in a properly designed and manufactured steam generator. All small leaks which are not terminated would appear to progress in stages which eventually pass through the transition size before they generate sufficient pressure to burst the rupture disc. For these reasons major emphasis is placed on the transition leak size.

2.0 SUMMARY

J. A. Ford and associates[1][2] performed a series of seven tests in which the leak rate varies in logical steps from 0.009 #/sec to 1.74 #/sec. It was found that above approximately 10^{-2} #/sec wastage began to appear on non-target tubes in addition to the target tube. This was attributed to the breakup of the main jet of water as it struck the target, thus generating smaller jets which deflected onto other tubes causing wastage wherever the right conditions for wastage existed. (See Section 4.1)

At around 0.8 #/sec a new phenomenon was observed and was described as follows in Reference 2:

"Test No. 53 was conducted with a leak rate of 0.79 #/sec. Analysis of the temperature chart showed a very unusual behavior in the target temperatures measured during the test. Immediately after the injection all of the thermocouples on the target tube indicated a rapid rise in temperature, and then all of the thermocouples indicated temperatures below 600°F, the bulk sodium temperature. Then for a period of approximately 10 seconds, temperatures remained below 600°F with only one or two of the thermocouples occasionally showing temperatures above 600°F. In the latter period of the injection all of the thermocouples generally indicated temperatures above 600°F. The low temperature readings were probably caused by the 2-inch spacing and the resulting larger diameter of the core of liquid in the jet that is cooled by flashing of a portion of the injected water."

The above could possibly describe a new phenomenon in which the leak has become large enough to void the target tube and cool it with steam. It is concluded in this study that this is the transition size leak for the particular test conditions of Test #53 in APDA Rig 10. The 2-inch target spacing that was used is significant and will be discussed in more detail later. (See Section 4.1 for more detail.)

The results of SUPERNOAH 5X run(3) at a leak rate of 0.88 #/sec appears to confirm the APDA transition leak size since the results were similar, i.e., intermittent steam blanketing at several locations in the vicinity of the target tube. (See Section 4.2.)

The key system parameters for Rig 10, SUPERNOAH and LLTR are listed below for comparison.

	RIG 10	SUPERNOAH	LLTR
Cover gas location	Vessel	Vessel	Surge Tank
Na pressure @ leak site, psia	30	31	160
Water pressure, psia	2650	2200	1700
Water temperature, °F	600	572	580

Note that Rig 10 and SUPERNOAH were nearly the same in all aspects, whereas LLTR has a much lower steam pressure and a much higher sodium pressure. It is concluded that roughly 0.80 #/sec was the transition leak for Rig 10 and SUPERNOAH based on an evaluation of the thermocouple readings during the test.

If the transition phenomenon results from a steam filled bubble that grows without reacting significantly with the sodium, then the strong parameter is the volumetric flow rate of steam displacing the sodium. Assuming 0.80 #/sec transition steam flow in Rig 10 and SUPERNOAH, the volumetric steam flow into sodium is ~4.5 ft^3/sec.

Assuming this same 4.5 ft^3/sec is required in LLTR to produce transition requires that the steam flow rate be 5.3 #/sec. The reason for this much higher flow rate in LLTR is the higher sodium pressure which produces steam roughly 6.4 times more dense than in Rig 10 or SUPERNOAH. (Section 5.2.1 shows the details of this calculation.)

However, if the steam reacts with the sodium, the volumetric flow rate of hydrogen into sodium is roughly 5 to 10 times larger in volume than the steam volume flow if the steam were to remain unreacted, assuming a 1900°F temperature for the hydrogen after the reaction. This produces a paradox since at transition a large bubble tries to form but when it forms it fills with unreacted steam which reduces the volumetric displacement of the sodium and slows transition. This could lead to instability at transition which could account for the periodic temperature spikes on the steam blanketed thermocouples in Rig 10 and SUPERNOAH.

If the same volumetric flow rate of hydrogen is assumed in LLTR as in Rig 10 or SUPERNOAH where all the water reacts to form hydrogen, then the LLTR Series II Test A-4 leak size would have to be 4.3 #/sec as compared to 0.8 #/sec. (See Section 5.2.2 for details.) Thus, it is concluded that the transition leak size in LLTR must fall between 4.3 #/sec and 5.3 #/sec which is in the range of or larger than the DEG leaks in Tests A-2 and A-6.

Flame-type jets with steam that is more dense by a factor of 6 might be reasoned to be roughly $\sqrt{1/6} = 0.40$ times the diameter and 0.16 times the area and because of the high density might penetrate much further into the sodium if left unobstructed. The result of higher sodium pressures may be much smaller wastage holes with faster penetration. Also, the leak size at which bounce-off and involvement of tubes other than the target tube occur may be much smaller. All small leak wastage tests run in the U.S. and abroad should be carefully reevaluated for pressures typical of real systems.

An attempt was made to reevaluate the LLTR Series I tests based on the premise that all holes up to and possibly including DEG size are jet flame types. A DEG leak, which is pancake shaped, differs considerably from the same leak flow directed out through a large round hole. Nevertheless, Series I DEG Test, SWR-1, in the short duration available, showed wastage characteristics similar in some respects to the smaller 0.8 #/sec leaks at low sodium pressures in Rig 10 and SUPERNOAH. (See Section 7.0.)

Series I Test SWR-2 was almost identical to SWR-1 except for the absence of any wastage. SWR-1 was at the bottom window region, whereas, SWR-2 was mid-length of the vessel where it was close enough to open one of the three panels on the upper rupture disc (RD-2). As a result SWR-2 undoubtedly had less sodium cascading through the leak site which might explain less wastage but not the absence of wastage. The leak-to-target spacing on SWR-2 was increased substantially from that of SWR-1 by tube bowing which could explain the absence of wastage. The APDA tests at transition size showed the reverse effect in which wastage at 2" spacing was severe compared to no damage at 1" spacing. One plausible explanation seems to be that the maximum damage spacing and transition leak size are changed in a major way by increased sodium pressure.

LLTR Series I Tests SWR-3, 4, and 6 located at the top of the vessel evacuated the sodium from around the leak site early in the large leak event but there was still slight wastage (~.004 inches) in the vicinity of the leaks. Since there was no tube bowing these tests had the same spacing as SWR-1 and lend credence to the possibility that jet flames persist in leaks up to and including DEG size if the tube spacing is normal and the sodium pressure is high. Confusing this conclusion somewhat is the fact that SWR-3, 4 and 6 were all run at the same general location near the top tube sheet such that the wastage was cumulative.

The Series I sodium thermocouple traces were examined for evidence of steam blanketing. The only evidence of steam blanketing was found in Tests SWR-3 and SWR-6 where some of the thermocouples indicated less than sodium temperature at roughly 2-3 seconds into the event after the sodium had been evacuated from the vessel. These late indications are not considered significant. It was concluded, based on the Series I thermocouple locations, that no steam blanketing was present in the DEG or larger leak sizes. (For more detail see Section 7.0.)

The effect of sodium pressure on the characteristics of steam jets applies over the full spectrum of steam conditions from sub-cooled water up to and including superheat. (See Figures 4 and 5.) Since shell-side pressures rise above the normal operating pressure at the leak site, investigation of the wastage phenomenon up to rupture disc burst pressures would appear to be highly desirable.

In References 9, 10, and 11 projections, explanations and rationale were given in support of the Series II leak size selections. These rationale are still sound. Tests A-3 and A-4 are the only two tests which involve jet flame performance in their selection. The recommendations for these two leaks are discussed in Section 3.0 of this report. (Detailed background discussion is presented in Section 9.0.)

Because of the small surge tank on LLTR it is estimated that Test A-4 will run 30-50 seconds from leak initiation out to the rupture disc burst time. The additional 30 seconds of leak injection after disc rupture will bring the total time up to 60-80 seconds. This is less than prototypical of CRBRP unless during the pre-burst period secondary leaks of sufficient magnitude develop to give an early burst time for the disc that is prototypical for CRBRP. Two methods for extending time are possible: one involving bleed flow from the surge tank to the reaction products tank, and one in which the sodium/cover gas interface is lowered into the LLTV to gain more gas space. (For more detail see Section 8.0.)

3.0 RECOMMENDATIONS

1) Series II Tests A-1a, A-1b, A-2, and A-6 are DEG leaks for which the previous rationale for leak size selection as contained in Reference 10 is still valid. Test A-5, which was tentatively set at 2 #/sec, also fits the rationale except that confirmation is required (Ref. 10) to prove that 2 #/sec is truly the largest leak which can be tested without rupturing the disc with the initial pressure spike. Reference 9 provided the basis for selection of the Test A-3 leak size of 0.1 #/sec. Until quantitative data is available on the effect of sodium pressure on jet-flame characteristics and wastage, it is recommended that Test A-3 be kept at 0.1 #/sec.

This leaves Test A-4. Since it appears from the discussion of sodium pressure effects summarized in Section 2.0 that the transition leak size may be in the range of the DEG size leak (Tests A-2 and A-6), it is recommended that Test A-4 be considered not a transition leak but rather a mid-range larger leak. Since A-4 is bracketed by A-3 (0.1 #/sec) and A-5 (2.0 #/sec), it is recommended that A-4 be sized at an intermediate value of 0.5 #/sec. (For more detail see Sections 5.0 and 9.0.)

2) A plastic model consisting of a pressure vessel with plastic tubes and tube support plates would aid greatly in visualizing and analyzing the effects of shell-side pressure, tube-side pressure, and hole size on leak dyanmics. The vessel could be built to 1/4 or 1/2 scale size with a minimum of four plastic tube support plates. A metal injection tube could be used to produce the high injection pressures required. Since the leaks to be investigated are relatively small (less than DEG) a simple solenoid valve could be used to initiate gas injection into dyed water. The vessel would require a scaled surge tank to simulate running times and pressure ramps. The vessel would require a simple rupture disc relief to a floor drain. The shell-side design pressure should be set as high as practically feasible to permit a study of jet dynamics and bubble formations as a function of vessel pressure level.

It is recommended that a test program be initiated using a plastic model where the leak size is allowed to vary over a large range of possible leak sizes. Besides giving the test engineer a clear visual idea of bubble and jet dynamics, it should be possible to define transition either qualitatively or analytically over a range of shell pressures. (See Section 5.0 for further discussion in support of a visual model.)

3) Since the shell-side pressure may have a significant effect on small leak impingement wastage, it is recommended that tests be run to determine the sodium pressure effect. (See Section 5.0 for background discussion and data.)

4) Due to the short running time available for Test A-4 it is recommended that a study be made to determine ways to increase the pressurization period in the surge tank. Possibilities include bleeding flow from the surge tank to the RPT or voiding the piping between the surge tank and the vessel with nitrogen cover gas. (See Section 8.0 for further detail on increasing the running time for Test A-4.)

4.0 EXISTING DATA

4.1 APDA Data

J. A. Ford and associates[1][2] ran a series of tests in APDA in the 1969-1970 time period which parallel closely in leak size selections the tests outlined for the LLTR Series II test group A. Table I shows the data from these runs. Liberty was taken in rearranging the test data in order of ascending leak sizes, placing the test numbering used at APDA out of sequence. The leak sizes start at .009 #/sec and build up in logical steps (left to right in Table I) to 1.74 #/sec. If the test conditions and test hardware had matched Series II the need for running the Series II tests would be obviated. Certainly if there is a transition size leak it should show up in the APDA test array.

As the leak rate was increased from very small leaks the wastage rate continued to increase until reaching leak rates of approximately 0.07 #/sec. Beyond this size the target tube wastage dropped off. Above leak rates of around 0.01 #/sec, wastage was found to occur on areas of the tube bundle located either adjacent to or behind the main target area. Where wastage was obtained on both the target and on adjacent tubes the target tube had the greater wastage. However, significant wastage rates were obtained on the tubes adjacent to the target tube, namely, 0.3 and 0.4 mil per second in tests #41 and #44 (0.07 #/sec) respectively. This same experience was confirmed by J. Bray of the UKAEA[4]. The reason projected for this multiple tube wastage is the breakup of the main jet of water into smaller jets which in some cases became optimum sized jets or sub-jets resulting in wastage of tubes other than the target tube.

At 0.23 #/sec (Test #42) it was reported that a significant rise in temperature occurred when the test was triggered, and none of the target thermocouples showed any decrease in temperature below that of the bulk sodium, indicating that steam blanketing had not occurred. Examination of the tube bundle after steam cleaning showed the presence of general wastage over a wide area. The deepest penetration of the target tube was approximately 29 mils (0.67 mils/sec wastage rate). Tubes A-2, A-3, A-4, A-5, and D-3 (see Figure 1) had wastage rates up to approximately 1 mil/sec, and the inner cylinder (shroud) wastage rate was 0.5 mil/sec. The inner cylinder wastage indicated that tube damage at distances greater than the cylinder distance are likely with the 0.23 #/sec leak size of Test #52.

Table 1. SUMMARY OF PRELIMINARY DATA FROM RIG-10 AND SUPER-NOAH 5X TESTS

	TEST NUMBERS							SUPER-NOAH 5X
	40	41	44	52	42	53	43	
SODIUM SYSTEM								
Flow rate (gpm)	400	400	400	400	400	400	400	0
Velocity past target tube (ft/sec)	2	2	2	2	2	2	2	±4.5
Bulk temperature (°F)	615	617	585	600	600	610	610	590
Sodium level above injection point (ft)	8.4	8.1	8.3	8.5	8.3	8.5	8.2	15
Plugging temperature (°F) – Before injection	395	400	400	400	385	400	320	—
After injection	460	425	>580	>620	>600	>635	>630	—
INJECTION WATER SYSTEM								
Water added (lb)	0.22	2.0	2.0	10	10	20	20	—
Temperature (°F)	615	617	585	600	600	600	610	572
Pressure (psig)	2650	2650	2650	2650	2650	2650	2650	2200
Orifice size (in.)	0.010	0.036	0.038	0.043	0.085	0.085	0.128	0.118
Length of capillary (in.)	0.285	0.285	0.285	0.31	0.285	0.31	0.285	—
Capillary length-to-diameter ratio (L/D)	2.85	7.92	7.5	7.2	3.35	3.7	2.23	—
Injection point-to-target spacing (in.)	1	1	1	2	1	2	1	—
Injection duration (sec)	24.5	28.0	14.5	43.0	16**	25.2	11.5	22
Injection rate (lb/sec) – Predicted	–	–	–	0.19	–	0.70	–	0.88
Actual	0.009	0.071	0.077 (Est)	0.23	0.63	0.79	1.74	—
RECIRCULATING WATER SYSTEM (Target Tube Coolant)								
Coolant	N_2	N_2	H_2O	N_2	N_2	N_2	N_2	H_2O
Pressure (psig)	100	100	2650	100	100	100	100	2200
Pressurization Period, Seconds	–	–	–	–	–	–	–	72
TARGET TUBE WASTAGE								
Tube material	2-1/4Cr-1Mo	2-1/4Cr-1Mo	2-1/4Cr-1Mo	2-1/4Cr-1Mo	2-1/4Cr-1Mo	2-1/4Cr-1Mo	2-1/4Cr-1Mo	—
Wastage pattern	(1)	(2)	(2)	General	None	General	None	Sec Failures
Depth of penetration (mils)	14	31	12	29	Negligible	11	Negligible	Full
Wastage rate (mils/sec)	0.57	1.11	0.83	0.67	–	0.44	–	—
Wastage rate (mils/lb) H_2O	63.6	15.5	6	2.9	–	0.55	–	—
Maximum measured tube temperature (°F)*	1380	1887	1749	1860	1901	1930	ND	—
Time of maximum temperature (sec)	15.9	3.3	4.4	26.3	15.0	26.5	ND	—
COVER GAS								
Pressure (psig)								
Before inection	6	5	5	5.7	5	5	5	10
During injection (peak)	16.5	19	12	~ 28	20	~ 25	32	130
Hydrogen concentration								
Before injection (ppm)	5,000	~0	~0	40,000	5,000	14,000	2,000	—
Peak during test (ppm)	44,000	370,000	275,000	480,000	282,000	311,000	198,000	—
Change in concentration (ppm)	39,000	370,000	275,000	440,000	277,000	297,000	196,000	—
Rate of change (ppm/sec)	201	4,017	3,630	5,700	5,719	6,400	4,020	—
Elapsed time between leak initiation and initial H_2 change (sec)	75	75	60	40	86	74	59	—
Elapsed time between leak initiation and peak concentration (sec)	270	206	196	176	150	160	150	—
RELIEF SYSTEM								
Rupture disc burst time (sec)	—	—	—	—	—	—	—	0.95

*The maximum temperature of 2060°F occurred on TC No. 22 on tube A-4 at 41.0 sec (Test No. 52). The maximum temperature of 2090°F occurred on TC No. 22 on tube A-4 at 20.5 sec (Test No. 53).

**Most of water injection appeared to be complete by this time as evidenced by sharp drop in reaction zone temperature.

(1) Broad shallow wasted area

(2) Toroidal-shaped with central plateau showing some wastage

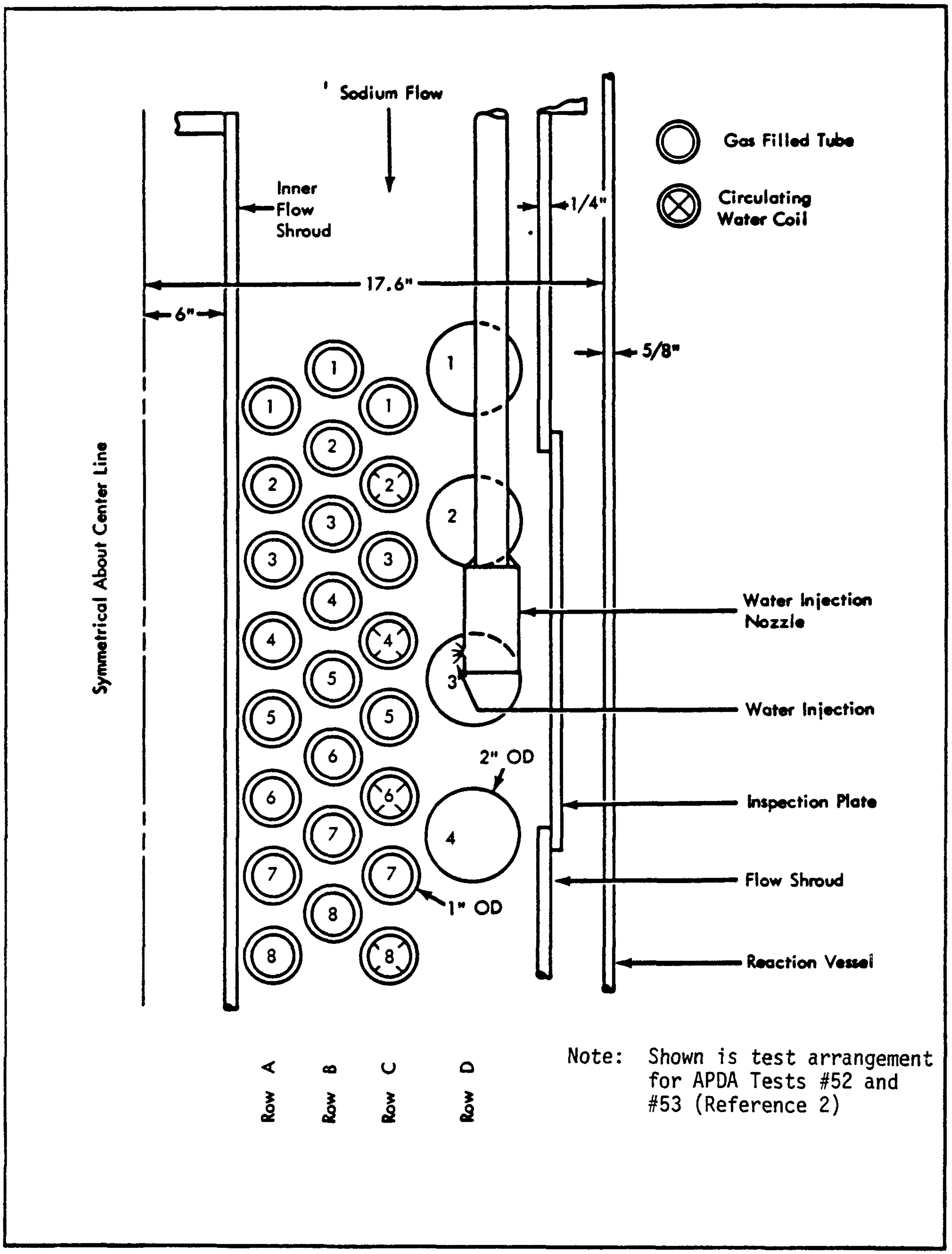


FIGURE 1. ELEVATION CROSS-SECTION OF TUBE BUNDLE ASSEMBLY (COPIED FROM APDA 261)

When the leak size was increased to 0.79 #/sec (Test #53) a new phenomenon was observed. After an initial temperature rise all the thermocouples on the tubes in the wastage region indicated temperatures below 600°F (the bulk sodium temperature). This continued for roughly 10 seconds with periodic rises above 600°F. The low temperatures were attributed to flashing and cooling by the steam core in the leak at the large leak size. This indicates that transition conditions had been achieved. Examination of the tube bundle showed that extensive wastage had occurred. The target tube had been wasted to a depth of 11 mils (0.44 mils/sec wastage rate). Tubes A-3, A-4, A-5, B-3, B-5 and C-4 had wastage rates up to approximately 1.0 mil/sec. The inner cylinder surface was wasted in the range of 10-15 mils (0.4 to 0.6 mils/sec). It is not clear whether the target tube wastage occurred during the main steam flow (0.79 #/sec) or at some lower flow as the injection tube blowdown occurred. With the target tube steam-blanketed as reported it is puzzling how it could have been wasted.

The two large leaks at 0.63 and 1.74 #/sec (Tests #42 and #43) showed only slight polishing of the tube in the target area. However, later tests (#52 and #53) with leaks of 0.23 and 0.79 #/sec showed general wastage on several tubes and the target tube in particular. The major difference between Tests #42 and #43 (minor wastage) and #52 and #53 (major wastage) was the target spacings of 1" and 2", respectively. One might think that 1" is too close for the larger leaks to be effective, whereas, 2" is getting into the damage zone for these leak sizes.

It appears from the test descriptions that the APDA tubes experienced the start of transition at about 0.8 #/sec. Quoted below are Ford's description and interpretation of this test series:

"This shift in the behavior can be explained on the basis of the core of liquid in the jet. For the lower leak rates, the argument was made that the maximum in the wastage curves was caused by the presence of a core of subcooled liquid that protects the surface from wastage and that this effect becomes more pronounced as the leak rate increases. This is evidenced by the change from a pit-type to a toroidal wastage pattern. At the closer spacing, the core of liquid at the higher leak rates is large enough to protect most of the surface from wastage, thus the occurrence of lower wastage rates as the leak rate increases. It has also been noted that the sodium-water reaction appears to occur over a very narrow band between the water-steam jet and the surrounding sodium. For large leaks and close target spacings, the injection fluid probably produces a spray of such magnitude that lower wastage rates are obtained. As the target is moved away from the leak it is conceivable that less spray is formed and that a part of the jet can be concentrated enough to cause appreciable wastage on the target. The appearance of wastage over a much wider area at these higher leak rates than those observed at closer spacings tends to support this theory. One additional observation that also supports this argument is that wastage began to occur on tubes in the rows behind the target row as the leak rate increases. This indicates that the primary jet from the capillary is broken up into smaller streams and in some cases a more damaging water-steam mixture is formed that causes wastage some distance away from the injection nozzle."

It appears from this description that a transition size leak represents a damaging condition in the leak zone and, if the duration is extended, could well result in several secondary tube failures. As the leak size increases above this size the time required to build system pressure to the rupture disc burst pressure decreases. Thus, for leaks initially of transition size or larger, the transition size leak has the longest dwell time. Leaks which grow from smaller sizes to the transition size through secondary or self-wastage would, of course, exist for somewhat longer periods. It should be noted, however, that 10 seconds of exposure in Rig 10 did not drill any holes. At the peak wastage rate observed, 0.60 mils/sec, it would take roughly 190 seconds to produce a secondary failure in a CRBRP tube.

4.2 SUPERNOAH Data

One of the five SUPERNOAH tests, test 5X, was run at roughly the transition leak size (0.88 #/sec) and was extensively described in Reference 3. This test ran for 84 seconds with primary injection lasting 22 seconds. The bundle flow, or secondary tube flow, was valved off at 12 seconds. Additional blowdown of the trapped water through secondary leaks lasted for 72 seconds with consequent pressurization of the sodium at the leak site. The rupture disc blew at 0.95 seconds at a pressure of 75 psi.

When removed and examined after the test the tube bundle showed extensive damage with several secondary leaks. The leak was aimed between adjacent tube rows and impinged directly on a tube two rows over from the leak. This tube was severely wasted on both the front and back sides allowing the leak to pass clear through the tube and impinge on the next tube in line four rows removed from the leak. The result was a large hole on the front face of this next tube in line.

One of the tubes adjacent to the leak suffered a grazing type wastage which generated a small leak about three seconds into the event. The larger leaks described above occurred after 84 seconds when most of the water was blown down. During the test a number of thermocouples indicated steam blanketing temperatures from time to time with an occasional upward spike indicating the possible return of the sodium.

The leak opened up in size from 3 mm to 9 mm during the test presumably from self wastage. The effect of this on the leak flow was not measured since the turbine meter in the injection line froze at 1.75 seconds and the dragmeter, which was designed for much larger leaks, was not recording.

SUPERNOAH 5X demonstrated that steam blanketing and several major secondary failures had occurred. Since the reported system conditions were almost identical to APDA Test #51, the confirmation by Test 5X of start of transition is interesting and convincing.

Both APDA Rig 10 and SUPERNOAH relieve the reaction products at the top of the vessel rather than at the bottom. If, for example, the vent had been at the bottom on Test 5X, after rupture disc bursting at 0.95 seconds, most of the sodium and reaction products would have vented in 5-7 seconds and only a very small secondary failure in the grazed adjacent tube would have been observed.

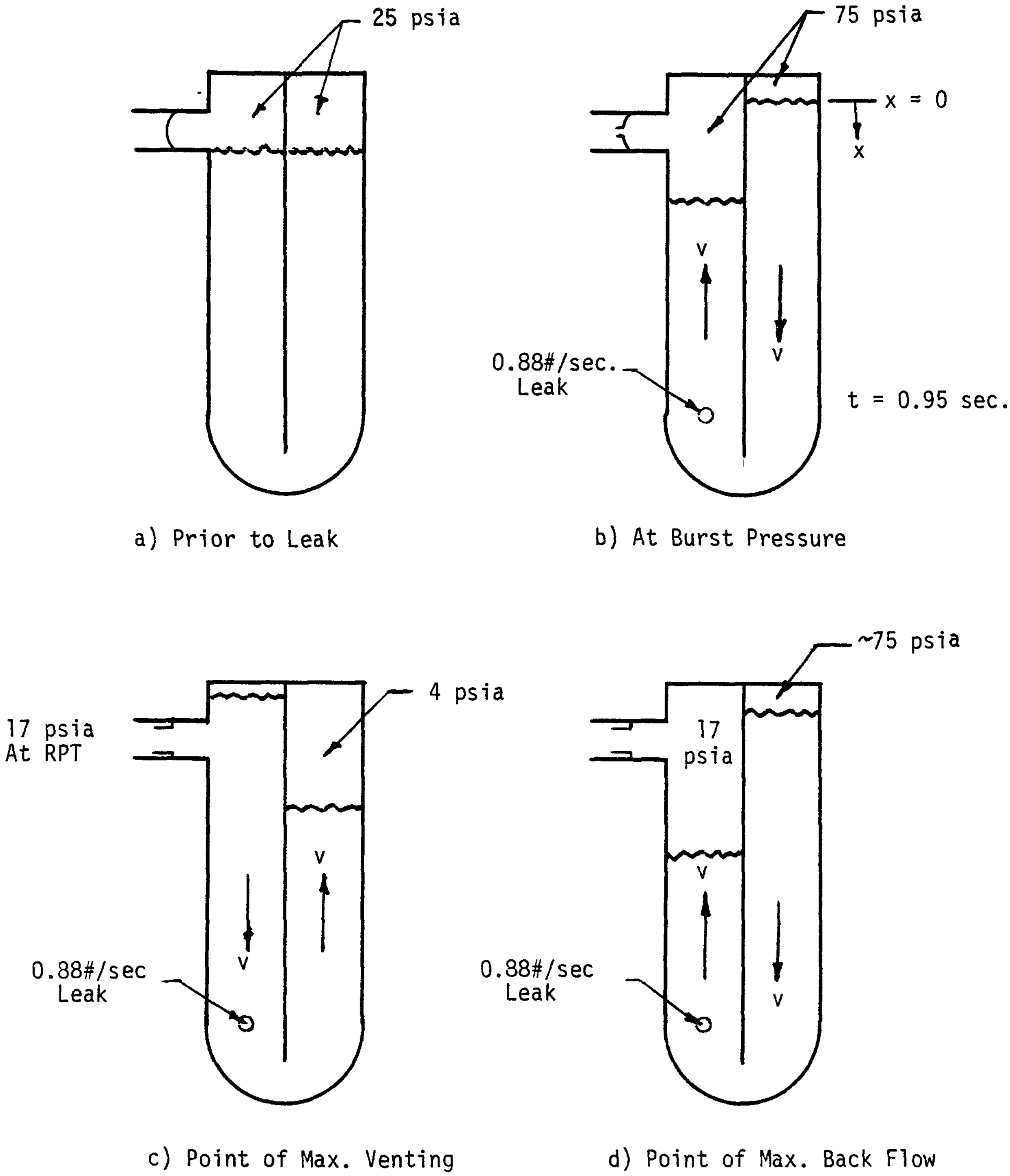
Figure 2 shows a sequence of hypothetical events projected for the evacuation of the U-tube test article used in Test 5X. At (a) the two cover gas spaces are equalized in both pressure and level just prior to the start of the leak. At 0.95 seconds when the bursting of the rupture disc is close at hand, the gas from the reaction site has joined the cover gas and pressurized to 75 psia. This causes 75 psia compression in the cover gas over the other leg of the U-tube as shown in (b). As the rupture disc bursts relief flow starts, and the gas pressure over the other leg of the U-tube starts to evacuate sodium around and through the leak site as shown at (c). The extent of this movement was of interest. Therefore, an approximate analysis of the type developed in Reference 5 was used based on rough estimates of flow areas, resistances and dimensions. The resulting displacement, velocity, acceleration and cover gas pressure are plotted in Figure 3. This analysis shows that the cover gas pressure reduced to 4 psi at the lowest pressure point generating a reversed pressure loading on the sodium column which returns it to near original condition prior to the burst rupture disc. It appears that the sodium column may oscillate back and forth through the leak site at least initially for a few cycles. But this analysis shows that a clean evacuation of the vessel does not occur, leaving sodium around the leak site and periodically flushing the area with fresh sodium. This probably occurs for the duration of the test as pressure surges keep the system unbalanced. This could have contributed to the more rapid and extensive damage as compared to Rig 10 results for which roughly 190 seconds appear to be required to generate the first secondary failure.

In conclusion, Currie states in Reference 3:

"The field of wastage was not as great as was feared before the test due to the existence of a non-damaging steam core in the jet. The main secondary leak, on tube 13, opened up when the initial leak rate dropped off, not during the time when the leak was in the intermediate range. The only penetration during the intermediate regime of the test was a very small hole probably in tube 8. Intermediate leaks present no greater threat to the environment, in the form of sodium release to atmosphere, than large leaks."

It's interesting that Currie does not attribute the major damage to the transition leak size and flow condition but to non-transition conditions that developed later in the test.

FIGURE 2. SUPERNOAH 5X VENTING CALCULATION SCENARIO



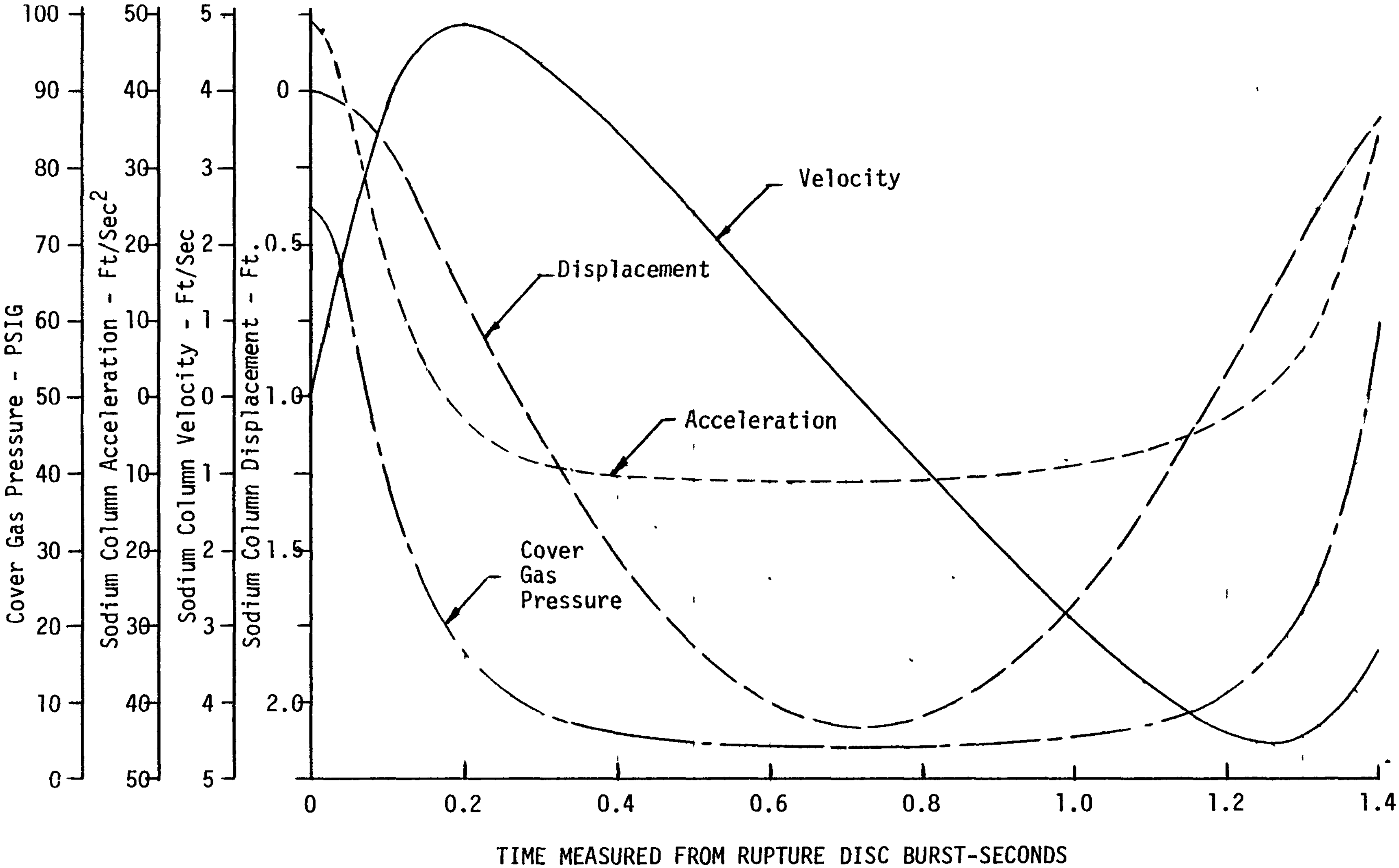


FIGURE 3. CALCULATED BLOWDOWN CHARACTERISTIC OF SUPERNOAH 5X TEST

5.0 RELATING EXISTING DATA TO TEST A-4 CONDITIONS

5.1 Analysis of Transition

One explanation for transition is the inability of the system to vent the steam and hydrogen formed quickly enough with the result that a large steam/hydrogen bubble develops around the immediate target tubes. At slightly larger size leaks this bubble causes continuous displacement of sodium near the leak site resulting in a growing steam and/or hydrogen void.

Based on this premise it was decided that the following mechanisms and parameters enter into analysis of when transition occurs:

1) Volumetric flow rate of steam into the reaction zone.
2) Consumption of part of this steam volume in the production of hydrogen which then joins the steam in the voiding process.
3) Bubble forces consisting of surface tension, internal vs external pressure loads, bouyancy forces, drag forces as the bubble grows into the sodium, and displacement forces required to move sodium through the system to make room for the bubble.

A quick literature search turned up a few references to bubble dynamics of which Reference 6 is a good survey paper. However, none of the analyses are directly applicable to the transition leak problem. Time did not permit the development of complex original analysis for this report. There is no assurance short of experimental verification that such analysis would predict the events at transition.

A transparent plastic test mockup of this phenomenon using water simulation would be extremely valuable with respect to visualizing the process and verification of analytical techniques.

As a rough approximate approach to the problem the list of variables above was studied and the most important parameter appeared to be the volumetric flow rate of steam/hydrogen into the reaction zone. Bubble bouyancy would vary slightly with gas and/or vapor density in the bubble, but the effect is second order when compared to sodium density. Bubble dynamics for the same volumetric flow rate should be very similar.

In order to avoid the question of what fraction of hydrogen and steam exists in the bubble the transition size for Test A-4 was extrapolated from transition in Rig 10 and SUPERNOAH based on all steam and then all hydrogen in order to bracket the leak size.

5.2 Selecting LLTR Series A-4 Leak Size

5.2.1 Based on 100% Steam in the Bubble

The volumetric production of steam, Q, is related to flow, W, and specific volume, v, by the simple relationship

$$Q = Wv \tag{1}$$

The blowdown of steam through an orifice, if taken after velocity recovery, is an adiabatic, or constant enthalpy, process. All three test programs, Rig 10, SUPERNOAH, and LLTR, involve the blowdown of subcooled water for which the enthalpy, h, upstream of the break can be approximated as the saturation enthalpy at the subcooled liquid temperature, i.e.,

$$h = h_f\ (Ts) \tag{2}$$

Downstream of the leak the enthalpy is still h from which the steam quality in the exit jet of steam can be calculated.

$$x = \frac{h-h_f}{h_{fg}} \tag{3}$$

In eq (3) h_f and h_{fg} are the saturated liquid and heat of vaporization enthalpies respectively for the steam evaluated at the local sodium pressure at the leak site. The initial enthalpy, h, is obtained from eq (2).

The specific volume of the steam jet prior to reaction with sodium is:

$$v = v_f + x\ v_{fg} \tag{4}$$

Where x is obtained from eq (3) and v_f and v_{fg} are the specific volumes of liquid and evaporation respectively for the steam evaluated at the sodium pressure.

Equations (1) through (4) provide the means for calculating the volumetric displacement rate for the steam jet in sodium assuming no reaction with the sodium.

If "W" and "v" are known for one experiment the same volumetric displacement can be assured in the other by the following, where subscript "o" denotes the known test data:

$$W = W_o(v_o/v) \tag{5}$$

Table II lists the data and calculations made possible by equations (1) through (5) for Rig 10 (Test #53), SUPERNOAH (Test 5X) and LLTR (Test #A-4). From this exercise it was found that the LLTR transition leak size based on equal volumetric flow rates of steam must be 5.3 #/sec.

5.2.2 Based On 100% Hydrogen in the Bubble

There are two principal sodium water reactions which produce different amounts of hydrogen as indicated below:

$$\begin{aligned} &Na + H_2O \rightarrow NaOH + 1/2\ H_2 \\ &18\#H_2O \rightarrow 1\#H_2 \\ &2Na + H_2O \rightarrow Na_2O + H_2 \\ &18\#H_2O \rightarrow 2\#H_2 \end{aligned} \tag{6}$$

The hydroxide reaction is most likely at the sodium temperature of Test A-4. Thus, 18 lbs of water are required to produce 1 lb of H_2.

The gas law can be used to calculate the specific volume of hydrogen:

$$v_{H2} = RT/P$$

where: $R = 766.8$ for hydrogen

Thus: $$v_{H2} = 766.8\ T/P \tag{7}$$

The volumetric production of hydrogen, Q, can be obtained from

$$Q = W_{H2}\ v_{H2} \tag{8}$$

TABLE II

COMPARISON OF LEAK CONDITIONS FOR TEST A-4
VS TEST #53 (APDA) AND TEST 5X (SUPERNOAH)

	Test #53 Rig 10	Test #5X SUPERNOAH	Test A-4 LLTR
Cover Gas Location	Vessel	Vessel	Vessel
Na Pressure @ Leak Site, psia	∿30	∿31	∿160
Water Pressure @ Leak Site, psia	2650	2200	1700
Water Temperature, °F	600	572	580
Mass Flow Rate, G, #/sec-ft^2	20,050	11,600	--
Enthalpy Upstream of Leak, BTU/#	617	578	589
Enthalpy Downstream of Leak, BTU/#	617	578	589
Steam Quality After Expansion, %	42	38	29
Specific Volume After Expansion, Ft^3/#	5.80	5.06	0.85
Volumetric Steam Leak Flow, Ft^3/sec	4.58	4.45	4.52
Orifice Diameter, Inches	0.085	0.118	--
Orifice Area, Sq. in.	0.00568	0.0109	--
Transition Leak Flow Rate, #/sec	0.79	0.88	5.31

Note: Evaluations were made for pretest sodium pressure. Sodium pressure is variable during test making comparisons more difficult. Numbers shown indicate trends only.

Substituting eqs (6) and (7) into (8)

$$Q = (1/18)W_{H_2O}\ (766.8\ T/P)$$

or $$Q = 42.60\ W_{H_2O}\ (T/P)$$

Assuming the hydrogen temperature will be 1900°F after the reaction *

$$Q = 1.0054 \times 10^5\ W_{H_2O}/P$$

Using subscript "0" to refer to Rig 10 and SUPERNOAH conditions and letting $Q = Q_o$ in the foregoing equation results in

$$(W_{H_2O})\ LLTR = W_o(P_{LLTR}/P_o)$$

$$= 0.80\ (160/30) = 4.3\ \#/sec$$

5.2.3 Conclusion

From the above calculations it was concluded that the transition leak size in LLTR will be in the range 4.3 to 5.3 #/sec.

*1900°F is approximately the highest temperature that has been reported in large leak SWR tests. This temperature is thought to be representative of approximately 100% reaction of sodium and water.

6.0 DISCUSSION OF TEST A-4 LEAK SELECTION

The roughly six times larger transition leak for LLTR vs existing leak data can be traced to the more dense gas and/or vapor condition in the sodium bubble of the LLTR tests. Figures 4 and 5 were prepared to show how the specific volume of the steam in the sodium is affected by sodium pressure. Figure 4 shows the results for blowdown from two conditions, namely, one at 2500 psia and 600°F and the other at 1700 psia and 580°F. Also shown are the conditions for APDA Test #53 and LLTR Test A-4. Figure 5 shows 1700 psia saturated steam and 950°F steam. This shows that the effect of sodium pressure on the specific volume of steam extends over the full spectrum of steam conditions from subcooled liquid to full superheat. Figure 6 shows the effect of sodium pressure on the specific volume of hydrogen where the specific volume is defined as the cu.ft. of hydrogen produced per pound of water reacted assuming 100% conversion. Two curves are shown corresponding to the two sodium/water reactions possible. Two things are evident from Figure 6. First, the volume displacement for a pound of fully reacted water is roughly 5 to 10 times larger than the displacement of unreacted steam at LLTR conditions. Second, the specific volume of hydrogen is affected in much the same manner as steam by the sodium pressure at the leak site.

The fact that the displacement by hydrogen is so much greater than by steam creates a paradox. The jet-type leak just short of transition is 100% reacted producing copious hydrogen. When the hydrogen begins to exclude sodium from the leak site water enters the leak site unreacted. The water can cool the reaction products and reduce their volume, thus allowing sodium to move back into the leak site. Assisting in the process is the reduced hydrogen generation rate. This has the characteristics of an unstable (possibly oscillating) system which may account for the occasional spikes on the steam blanketed thermocouples observed in both Rig 10 and SUPERNOAH.

For the purposes of this report the sodium pressure chosen for discussion was pre-test. In the cases of Rig 10 and SUPERNOAH there was an early pressure relief through the rupture disc which produced low pressures up to the time of the first large secondary leak. In LLTR the leak will continue for roughly 40-50 seconds before the disc relieves the pressure. In the meantime, the pressure is rising from 160 to ~340 psia. Figure 5 and Table II evaluation techniques indicate that at 340 psia the transition leak size for Test A-4 should be about 12.7 #/sec

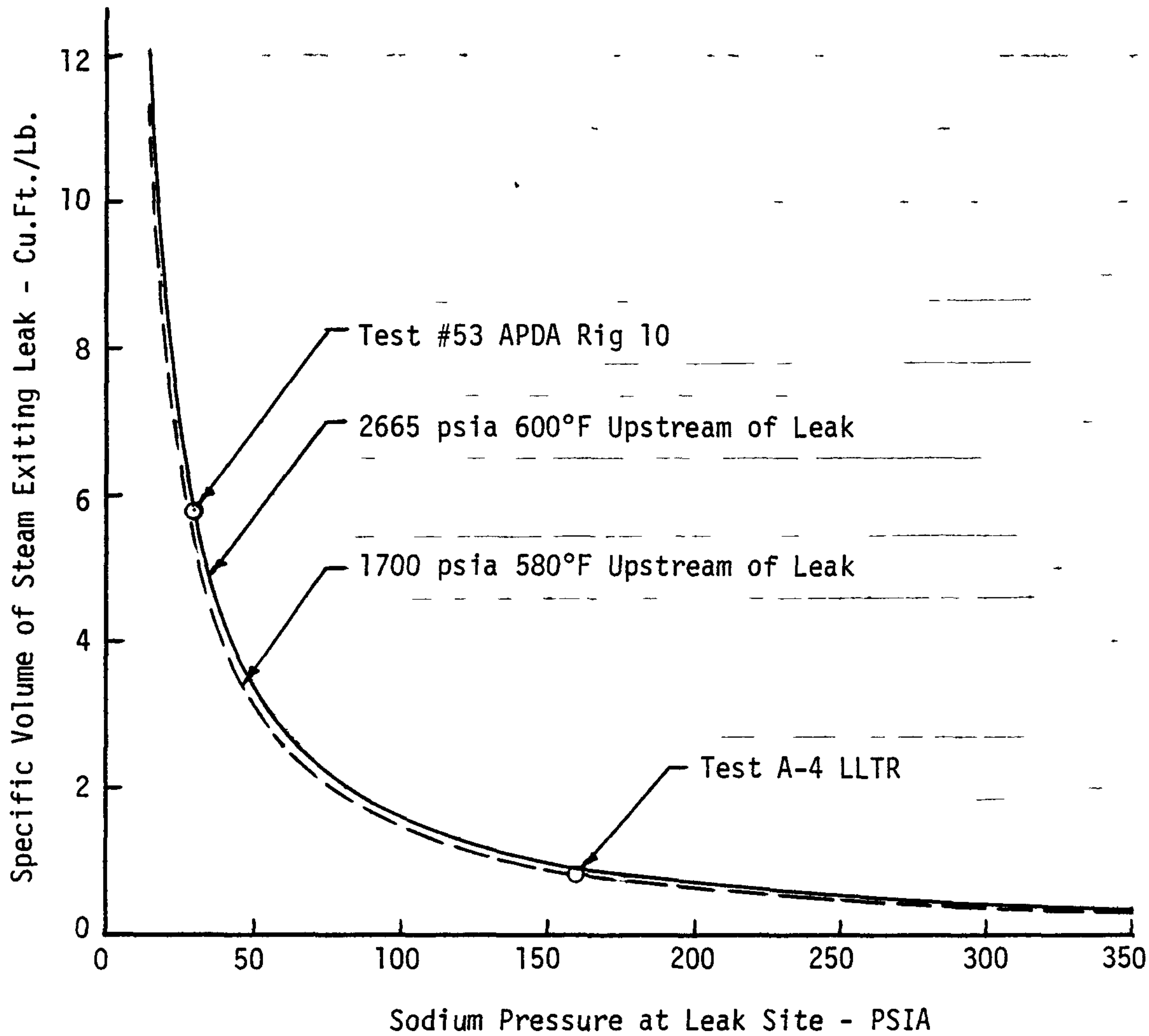


FIGURE 4. COMPARISON OF STEAM SPECIFIC VOLUME IN LEAKS FOR TEST #53 (APDA) AND TEST A-4 (LLTR)

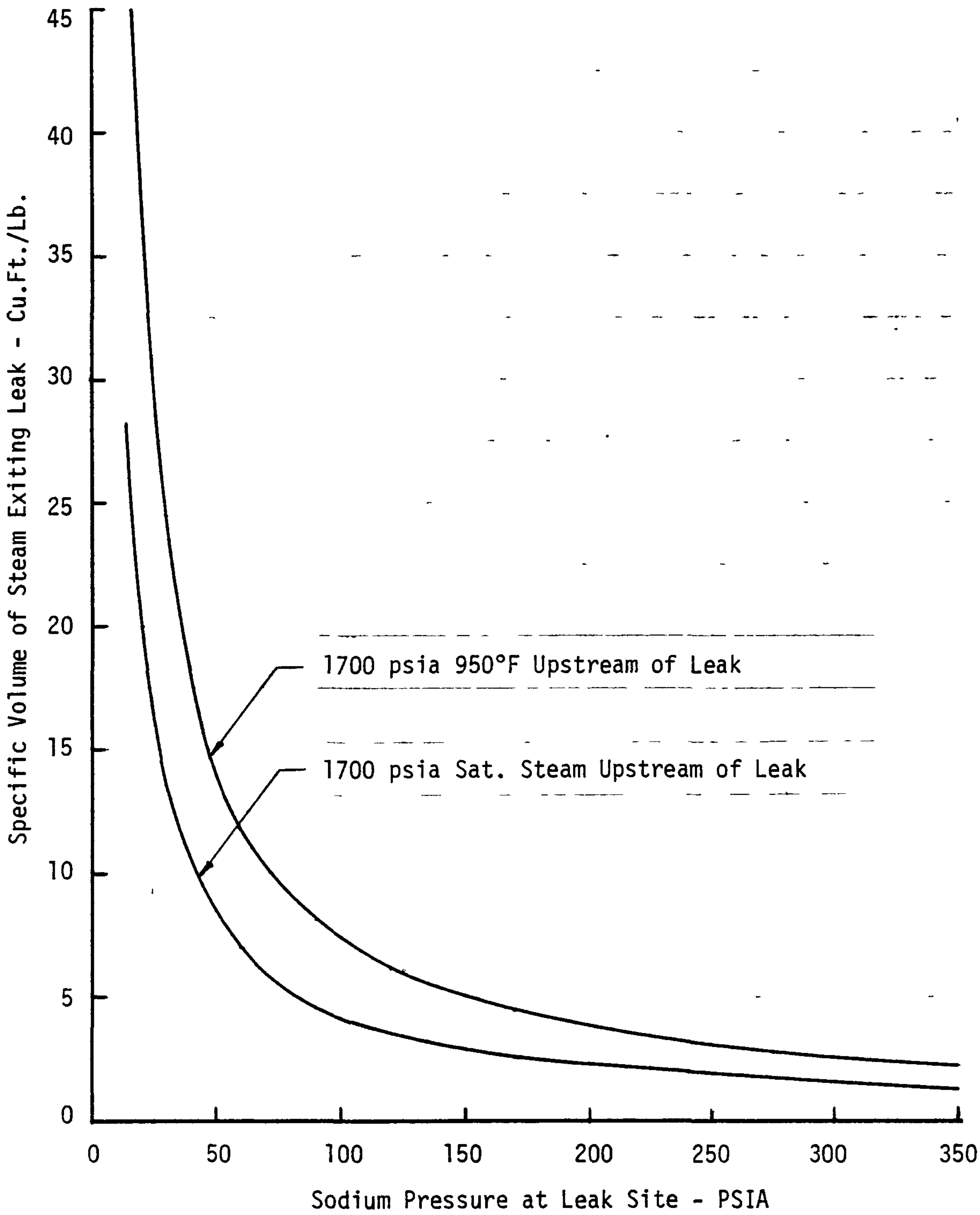


FIGURE 5. SUPERHEATED STEAM LEAKS - EFFECT OF SODIUM PRESSURE ON SPECIFIC VOLUME OF STEAM

Note: Curves Based on 100% Conversion of Steam Jet

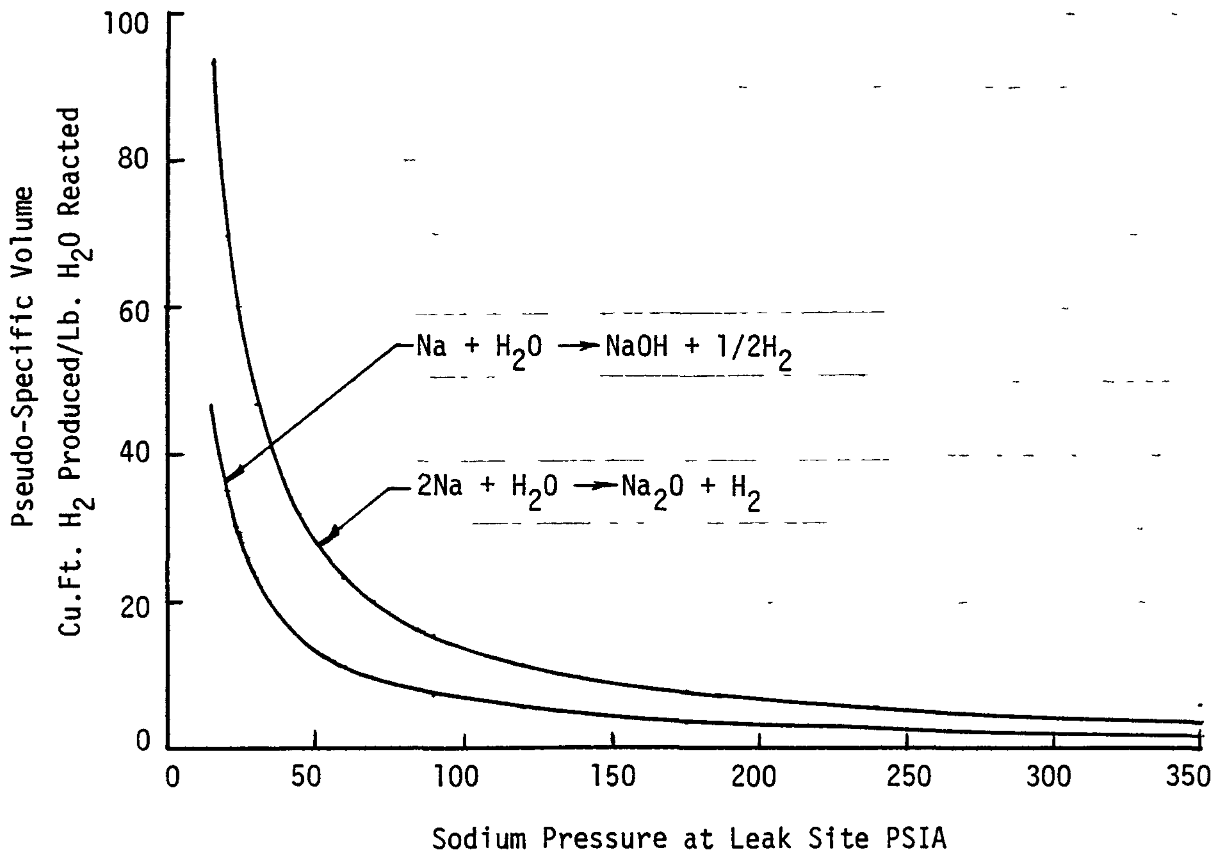


FIGURE 6. EFFECT OF SODIUM PRESSURE ON VOLUME OF HYDROGEN PRODUCED AT LEAK SITE

which is well beyond DEG size. Once the rupture disc blows there will be 30 seconds of blowdown leak flow during which the sodium pressure is almost at RPT pressure. Transition during this blowdown period has no meaning because the sodium will have drained off rapidly after the disc burst.

The conclusion from this analysis is that transition in LLTV/LLTI in Series II is probably not going to occur up to DEG size leaks. In any event there is no clear procedure at this point in time for predicting it. Therefore, a leak in the 0.8 #/sec range no longer has meaning for Series II, and it is recommended that Test A-4 be run at 0.5 #/sec instead. This will provide a more ordered spread in the range between Test A-3 (0.1 #/sec) and Test A-5 (2 #/sec). Test A-4 will then be 5 times larger than A-3 and 4 times smaller than A-5. If transition does occur in the Series II Group A tests, it should be bracketed by the leak sizes proposed.

The orifice size required to produce 5.3 #/sec is purposely left blank in Table II because at that flow rate the fluid velocity approaching the leak is over 150 ft/sec. Once the leak is initiated there will no longer be 1700 psia pressure in the tube due to the high injection system pressure losses. A RELAP evaluation is required to establish the orifice area for this size leak.

The reported leak areas and flow rates for Tests #53 and #5X in Table II seem incompatible with each other. Shown for comparison in Table II are the calculated mass flow rates for both tests obtained from:

$$G = W/A$$

Since both tests were run under flashing subcooled water conditions with roughly the same upstream pressure, both G values should be close to the same, yet Test #5X had a G value half that of Test #53. Since APDA measured their flow rate, whereas, SUPERNOAH had no measurements, it is reasonable to suspect that the Test 5X flow may have been greater than reported.

7.0 DISCUSSION OF LLTR SERIES I TESTS

If it is true that jet flames persist in the LLTR tests at high sodium pressures and high flows (DEG size), then jet flames should have been present in most or all of the Series I tests. In this regard test SWR#1 was of special interest since there was a wastage pattern developing which had some of the same characteristics as Test #53 in Rig 10 and Test 5X in SUPERNOAH. Figure 7, taken from Reference 8, shows the position of the DEG leaks for tests SWR-1 and SWR-2, namely, tubes 324 and 421 respectively. SWR-2 showed some polishing of surrounding tubes but not wastage, whereas, SWR-1 damaged five tubes ranging almost 360° around the DEG tube. DEG leaks are believed to give a 360° pancake type leak jet such that the wide spread of the wastage was not surprising. The fact that adjacent tubes were spared and wastage damage occurred several tube rows away, resembles Rig 10 experiences. However, the DEG flow rate in this instance was in the range of 2-3#/sec. The portion of this flow impacting on a single adjacent tube was calculated to be $\sim$0.3 #/sec, which leads to confusion in the interpretations, since this is less than the flow in APDA Test #52. The leak site pressure history for SWR-1 is shown in Figure 8 to vary from 150 to 400 psi during the test.

A comparison of a 360° pancake type DEG leak with a directed flow from a hole may be meaningless due to the large differences in the two conditions. It has always been the belief that a DEG leak produces piston type expulsion of the sodium. If this were the case, then no wastage should have occurred in SWR-1. The fact that SWR-1 was at the bottom just above the relief nozzle and the vessel was solid packed, means that sodium held above the leak had to cascade through the leak zone. This may be one explanation for the wastage pattern produced.

Test SWR-2 was also a DEG leak but located higher in the vessel, roughly at mid-span. Figure 9 shows a trace of the leak site pressure for SWR-2. If a tracing of Figure 8 is laid over Figure 9 it will show that the two leak site pressure histories were remarkably near to being identical. SWR-2 had a smaller amount of sodium trapped above the leak.

Why then did SWR-2 not show any wastage damage? One explanation may be that all the tubes immediately adjacent to the DEG were severely bowed outward on SWR-2, thus increasing the leak-to-target spacing. This tube bowing is shown clearly in Figures

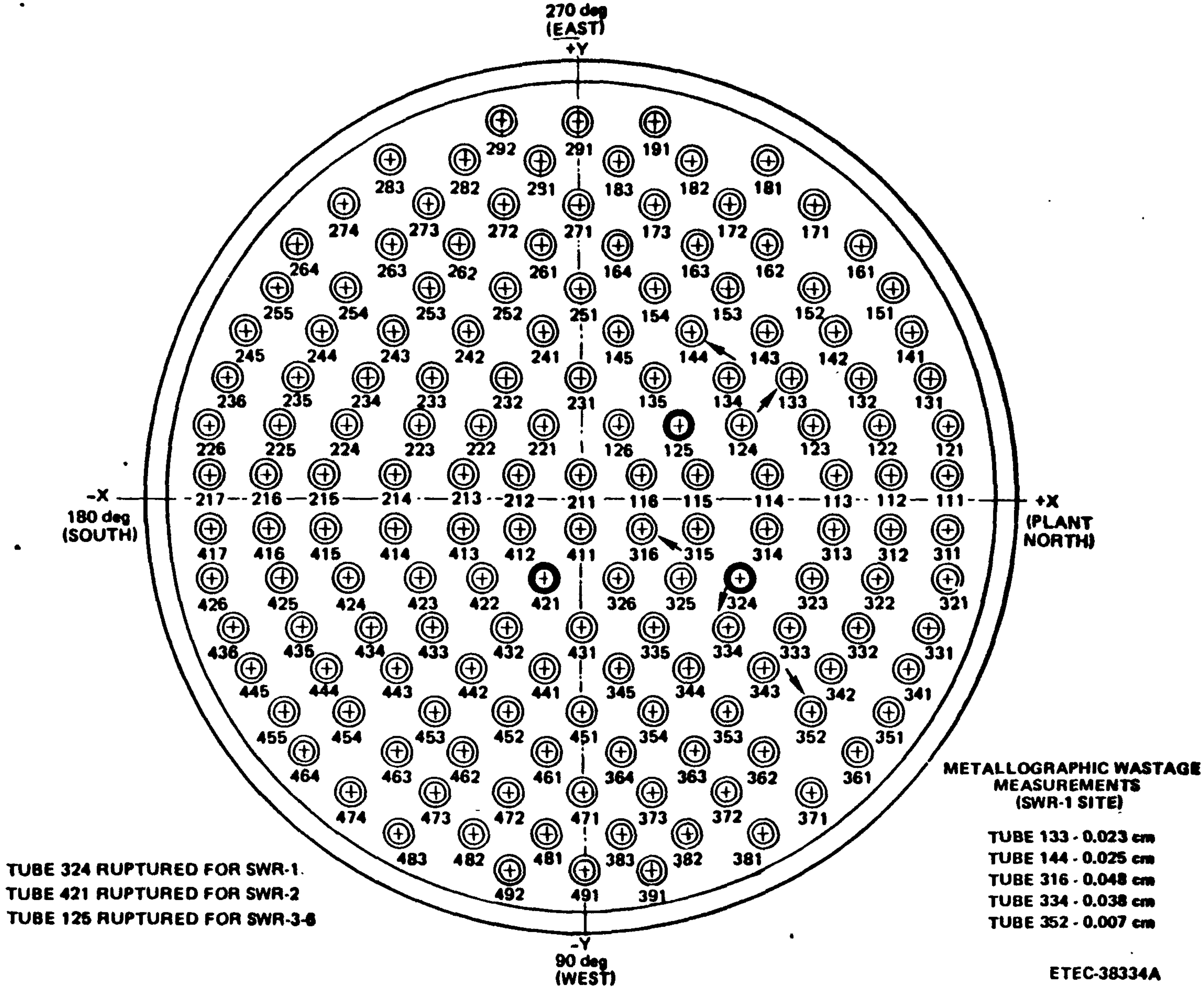


Figure 7. MSG Tube Number Plan

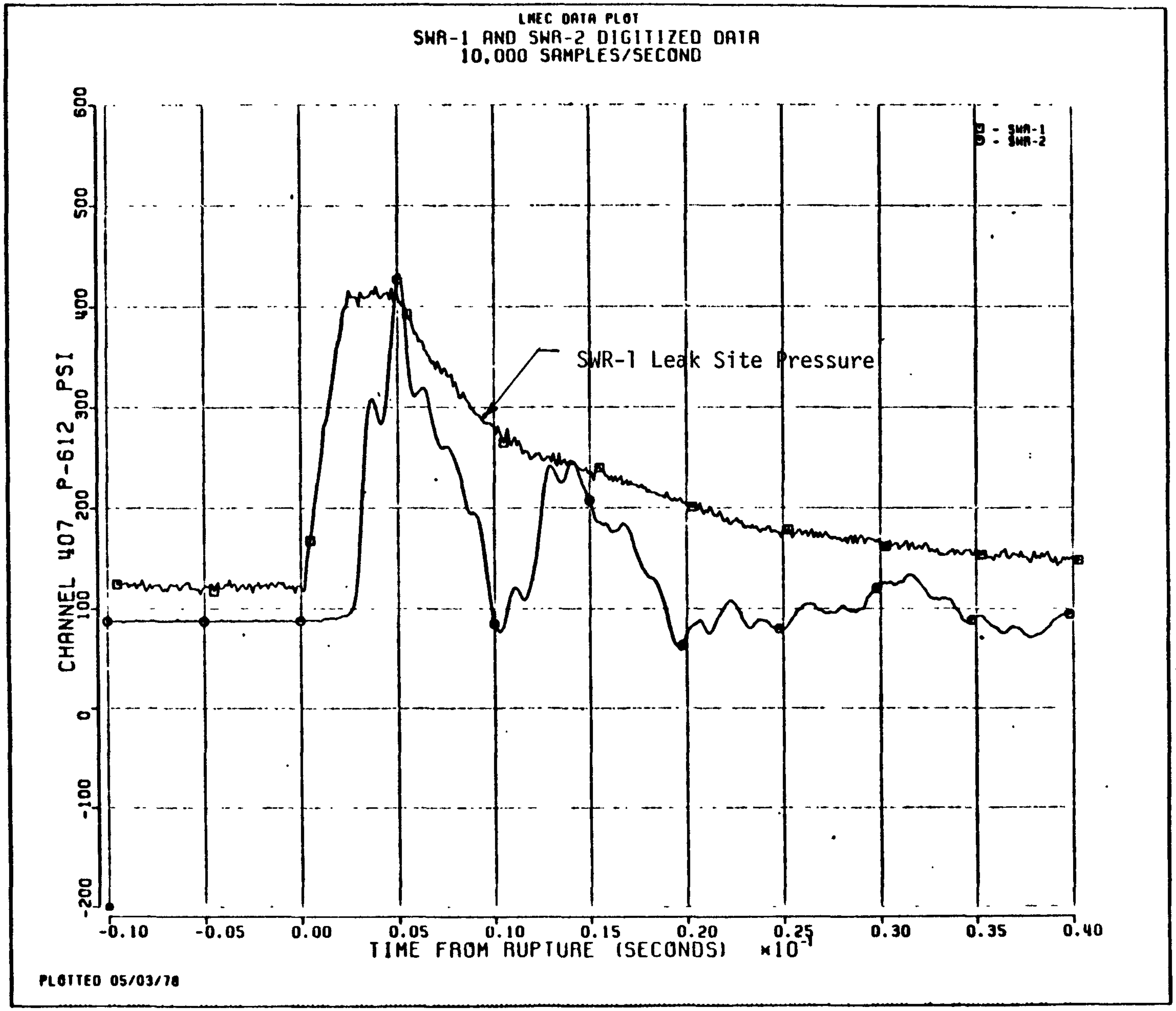


Figure 8. **Pressures at Location P-612 During SWR-1 and -2**

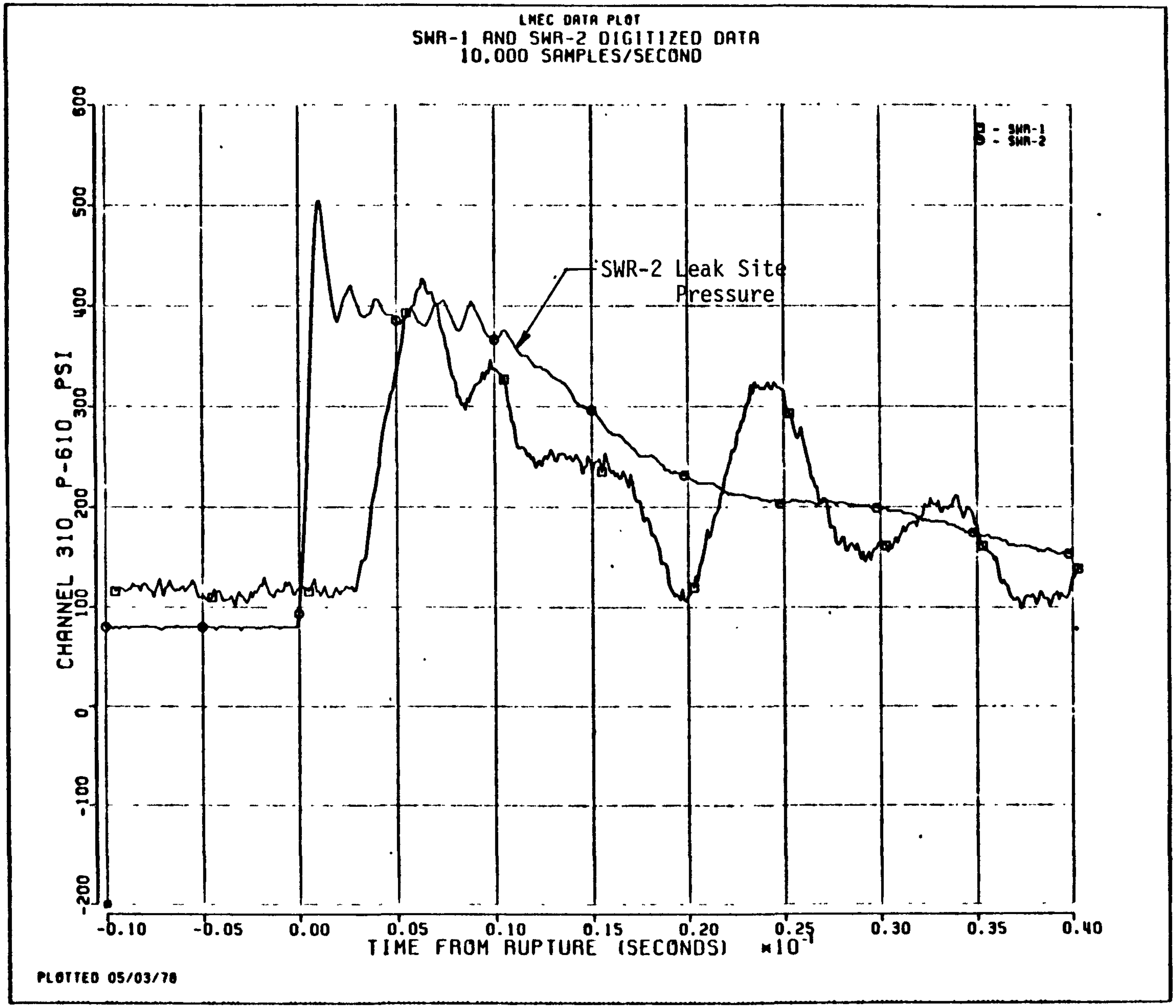


Figure 9. **Pressures at Location P-610 During SWR-1 and -2**

9 and 10 in Reference 8. Another possible explanation may be that the sodium in SWR-2 may not have cascaded through the leak zone to the same degree as in SWR-1 since the upper rupture disc (RD-2) in SWR-2 had blown out one of its three panels, whereas, it remained intact in SWR-1.

APDA Tests #42 and #43 (Table I) were run with a 1-inch spacing with very little wastage damage, whereas, Tests #52 and #53 were increased to 2-inch spacing with major wastage. At first this was thought to possibly explain SWR-1 vs SWR-2 wastage, except it will be noted that the reverse effect occurred - the closer spacing of SWR-1 received the most damage.

The answer could well be that leaks into high pressure sodium behave radically different from tests in low pressure sodium, and the critical leak-to-target spacings are much longer at the higher pressures. This was the only plausible explanation that could be developed for this interesting anomaly.

Tests SWR-3, 4, and 6 were run in the top end of the vessel, such that the sodium cleared the region of the leak very early in the event with little time for significant wastage. Interestingly, all three of these tests showed slight wastage cummulative < 0.004 inches in the vicinity of the leak. In these tests there was no detectable tube bowing due to the leaks. As a result the target spacing from the leak matched SWR-1. This may be interpreted as providing verification of some jet type flame action at this tube spacing at high sodium pressures. Unfortunately, all three tests were run at the same location which confuses the interpretation. However, based on past experience, these large DEG leaks would have been expected to produce instant voiding conditions with no evidence of wastage.

A study of the internal sodium thermocouples in all five Series I sodium/water tests showed no evidence of any steam blanketing at the T/C locations. Evidence of steam blanketing did show up on Tests SWR-3 and SWR-6 but it was 3 seconds into the event after the sodium had vented. This is not considered significant since it does not fit the definition of transition. The fact that no transition type steam blanketing occurred in these DEG and larger tests strengthens the conclusion that transition never occurred.

8.0 RUNNING TIME FOR TEST A-4

In Reference 9 curves were shown for estimating the time required to pressurize the surge tank to the rupture disc burst pressure. This analysis was initiated with a 2.52 cu.ft. heel of sodium in the bottom of the surge tank. As sodium is added to the surge tank the cover gas pressure increases adiabatically and a void opens up at the leak site equal to the amount of sodium added to the surge tank. The cover gas pressure in the surge tank must balance the pressure in the void. With the cover gas pressure known from the adiabatic compression, the void pressure is calculated at the leak site. The void pressure and volume are then used to calculate the amount of water flow and hydrogen generation required to fill the void volume at the pressure that is calculated. The hydrogen generation is based on the NaOH reaction and the pressure is calculated from the gas law, PV = NRT.

The resulting data is plotted in Figure 10 based on two hydrogen temperatures at the leak site, 590°F and 1200°F. At a leak rate of 0.5 #/sec as selected for Test A-4, Figure 10 shows that the burst time ranges from 32 to 50 seconds. An additional 30 seconds of injection will be added on after the disc bursts bringing the total running time up to 60 to 80 seconds. This assumes that no major secondary failures occur during this period. If they do, the disc will burst earlier than predicted above and the test can be considered prototypical. If, however, no secondary failures occur, the test would require some interpretation and extrapolation, since in CRBRP, the running time would have been many times longer. To insure the longest practical running times for Test A-4, two steps can be taken either singly or in combination. One consists of bleeding flow from the vent line in the top of the surge tank back to the reaction product tank (RPT). This can be accomplished by installing rupture disc RD-4 in this line set to burst at ∼250 psi. Provision is available for the installation of RD-4. Time will be required to calculate this case and determine if it is practical and how much time is gained. The second method for extending time is to move the cover gas boundary with the sodium back into the pressure vessel, such that the upper portion of the vessel and all the connecting piping up to the surge tank are filled with nitrogen. This is estimated to roughly double the running time. The disadvantage of this approach is the conversion from a solid-packed vessel to a cover gas vessel with a rather small amount of sodium left above the leak to fill the additional cover gas volume.

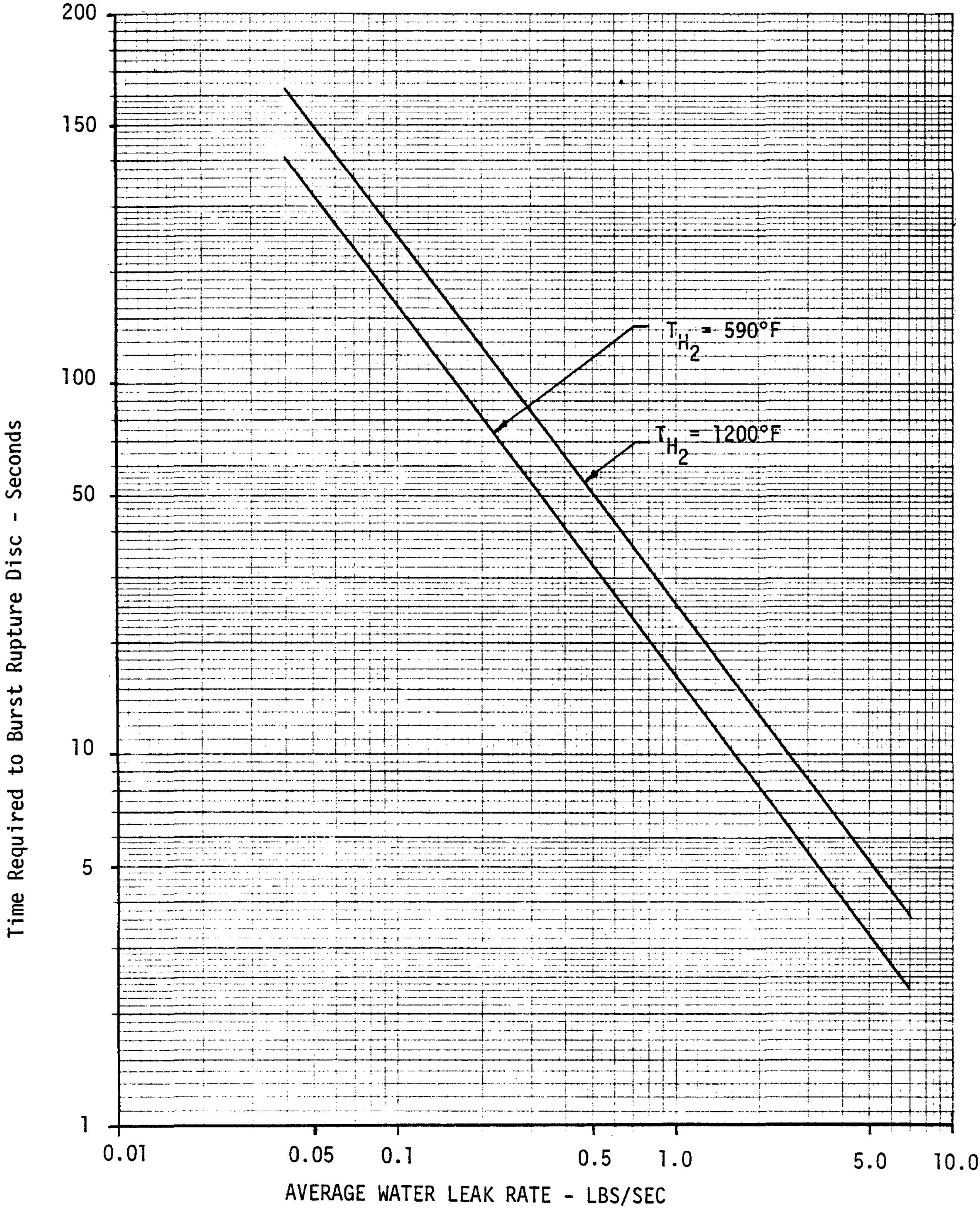


Figure 10. Characteristics of Time to Burst Rupture Disc vs Water Leak Rate

It is recommended that a more detailed study of both methods for extending running time on Test A-4 be made and implemented if they can be shown to be practical and safe.

In Section 5.2.2 a high-side hydrogen temperature of 1900°F was used when evaluating the transition leak size. The 1200°F hydrogen assumed here is an attempt to account for partial reactions and agrees well with measured temperatures in the Series I Tests.

9.0 EFFECT OF SODIUM PRESSURES ON LEAK SIZES SELECTED FOR SERIES II TESTS

Rationales were developed in References 9, 10 and 11 in support of the test selections made for the Series II tests in the LLTR. The rationale given in support of the DEG tests (A-1a, A-1b, A-2 and A-6) is still valid. The gas tests, A-1a and A-1b still provide a good non-destructive shakedown of the LLTR while producing good data on pressure levels and effects of two rupture disc designs. The two sodium water tests at DEG size (A-2 and A-6), one at the vessel centerline and one next to the shroud, still represent the largest achievable water leaks while the two positions center and edge help define the effects of radial positions on pressure levels and shroud damage.

The rationale given for Test A-5 was a large leak with an initial pressure spike which is just below the threshold for bursting the rupture disc. This size has tentatively been set at 2 #/sec but this requires further evaluation and study for final confirmation following completion of Test A-2. The rationale for selecting Test A-5 is still valid.

Remaining are the two intermediate leak sizes, Tests A-3 and A-4, for which the rationales for leak size selection were based on existing small and large leak tests. Reference 9 provided the basis for selection of the A-3 leak size as the size which would give the most rapid and extensive tertiary damage. Until quantitative data on the effect of sodium pressure on jet-flame characteristics and wastage is available, it is recommended that Test A-3 be kept at 0.1 #/sec.

The rationale for selecting the Test A-4 leak size was to create a leak at the point of transition from small leak jet flames to large leak voiding. Since this study indicates that the transition leak size may be in the range of the DEG size leak (to be examined in Tests A-2 and A-6), the 0.8 #/sec tentatively chosen in

Reference 11 no longer has special significance. Therefore, the recommendation is made that A-4 be considered not a transition size leak but a mid-range larger leak and sized to fit roughly midway between Test A-3 at 0.1 #/sec and Test A-5 at 2.0 #/sec. A size of 0.5 #/sec was selected. While being five times larger than A-3 and four times smaller than A-5, it is still close enough to the old tentative value of 0.8 #/sec that steam blanketing may still occur if the Series II tests demonstrate that there is little sodium pressure effect on the transition leak size.

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