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SUMMARY OF RESULTS FROM VELOCITY
PROFILE TESTS AND WASTAGE TESTS IN SUPPORT
OF LLTR SERIES II TEST A-4

by

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1.0 INTRODUCTION AND PROGRAM OBJECTIVES

An experimental program was completed in which velocity profiles and wastage phenomena were measured in support of LLTR Series II Test A-4. The primary objectives of the program were:--

- a) To recommend an orifice shape and size which would give the greatest probability of penetrating two or more tubes simultaneously (i.e., within a fraction of one second).
- b) To recommend an orifice fabrication technique for the LLTI.

The approach in the program was to measure velocity profiles for typical orifice geometries, and attempt to correlate these velocity profiles with measured wastage damage from identical orifice geometries.

The test program concentrated on slit geometries; the assumption being made that circumferential slits have the greatest probability of impinging equally onto adjacent tubes. Simple geometric examination of the tube array suggested the minimum jet width to cover two tubes will be $\sim 60^\circ$. Early test data indicated that the width should be increased and tests were made with slits up to 120° . All other test conditions were chosen to be as similar as possible to those expected in the LLTR.

2.0 DESCRIPTION OF TEST EQUIPMENT

A specially designed and fabricated test rig was used in the sodium-water reaction part of the program. This was the Sodium-Water Experimental Apparatus (Temporary), or the SWEAT rig. A fifty-five gallon drum about two-thirds full of sodium was wrapped with trace heaters and lightly insulated. The assembly was inserted into a slightly larger stainless steel drum, and a cover placed over the s/s container. This cover had provision for venting reaction gases, and an opening through which the test article could be inserted into the sodium filled drum. Other penetrations in the cover were used

to insert thermocouples to monitor the sodium temperature. This assembly was then placed in a large, quarter inch plate, iron tray. The cover was firmly chained to this tray. The SWEAT rig was located in an existing sodium disposal cell. The cell has double four inch thick windows allowing viewing of the rig during the experiment. The schematic diagram for the SWEAT rig is shown in Figure 1.

The water injection system was modified during the early tests to reduce pressure losses in the injection line. From Test S4 onwards the injection pressure was close to the required 1700 psi. A five litre reservoir was filled with water, and pressurized with Argon gas from a "twelve-pack" of compressed gas cylinders through a half inch diameter line. A half inch line from the base of the reservoir was isolated from the test assembly by a half inch ball valve with rapid-opening lever action. The final connecting pipe to the injection tube was fabricated from quarter inch pipe and included 8 feet coiled beneath the sodium level as a heat exchanger. At the inlet to the test article an in-line 1/16 inch diameter ch/AL thermocouple monitored the injected water temperature. During Test S4 when the half-inch ball valve was opened, a substantial acoustic pressure pulse was observed in the test rig. The injection system was further modified, with a quarter inch quick opening (toggle) valve bypassing the ball valve for Tests S5 and S6. To initiate a test this valve was opened, followed immediately ($<1/2$ sec) by the ball valve. The quantity of water injected during a test was obtained from the amount required to refill the cylinder to a known level. Normally, several injections were made sequentially to increase the test time. The reservoir was refilled between the injections.

Velocity profiles were measured using a specially fabricated rig based on a 1/16 inch diameter pitot tube. The pitot tube could be positioned in the space ahead of the test article using a holder fabricated from a microscope stage. The precise position of the pitot tube was known from the vernier scales to ~ 0.1 mm. in the x, y, and z directions. A further degree of manipulation was obtained by fitting the test injector into a rotating stage; the angular profile of the jet was measured using a stationary pitot tube and rotating the injector.

Figure 1 SWEAT Rig Schematic

3.0 TEST RESULTS

3.1 Sodium-Water Reaction Tests

Six tests were completed in the SWEAT rig. Injection details are summarized in Table 1. Each test will be briefly summarized.

TEST #S1 (shakedown): The target tubes were thinned to 0.020 inch wall thickness from the original 0.109 inch. Water was injected through a 0.040 inch diameter hole, and directed against a second row tube. The target tubes were pressurized to ~1600 psig, and loss of pressure after 14 seconds indicated tube penetration. Following this test changes were made to the SWEAT rig and injection system to improve test accuracy.

TEST #S2 (90° slit): Experimental difficulties with the injection system caused the orifice injection pressure to be reduced to a few hundred p.s.i. It is probable that low pressure steam was injected through the orifice. Significant wastage of the second row target tube occurred, with insignificant damage to the first row tubes. Self-wastage of the injection orifice also occurred. The injection system was redesigned following this test to minimize pressure loss through the injection lines.

TEST #S3 (90° slit): The test was initiated and a minor acoustic pressure pulse was noted. The first injection of ~4 lbs was completed, and while the reservoir was being refilled the target tube pressure fell to ambient from 1700 psig over ~ ten seconds. The bundle was removed; the second row target tube was missing. Another target tube was fitted into the bundle, and the assembly re-inserted into the rig. A second injection was made, with very similar results to the first. (the target tube had been ejected). The fitting for the target tube was found to be defective which allowed the tube to be ejected. The test was terminated at this point. Insignificant wastage of the first row tubes was found. Following the test the injection system was further modified to ensure full injection pressure.

TABLE 1 SWEAT RIG TESTS

Test #	Orifice Geometry	Orifice Size	H ₂ O Injected	Time of Injection	Injection Rate
S1	Circular	0.040 dia.	--	14 sec	--
S2	Circ. Slit	90°x0.010"	3 3/4 lb	87 sec	0.04 lbs/sec
S3	"	90°x0.017"	8 lb	19 sec	0.42 lbs/sec
S4	"	90°x0.016"	2 lb	5 sec	0.40 lbs/sec
S5	"	120°x0.017"	21 1/2 lb	30 sec	0.73 lbs/sec
S6	"	120°x0.016"	30 lb	46 sec	0.64 lbs/sec

TEST #S4 (90° Slit): Upon initiating the injection a significant acoustic pressure pulse was noted. This caused experimental difficulties and the test was aborted after ~4.5 seconds. The test bundle was removed and it was found that significant distortion of the injection tube had occurred. The injection system was again modified to reduce the acoustic pressure.

TEST #S5 (120° slit): The injection tube for this test was fabricated with a circumferential slit of 120°, and an axial width of 0.008 inches. It was carefully aligned to give a symmetrical pattern covering the first row target tubes. The injection rate was much higher than expected. After an injection time of ~30 seconds the test was stopped and the test section removed. Wastage damage to all three target tubes was measured, and is shown diagrammatically in Figure 2. Wastage of a support rod was also found, indicating wastage was possible outside the region of the target tubes. The injection orifice was found to have a width of 0.017 inch, and post-test injection tests confirmed this was the size of the orifice during the test. It was obvious that a 120° injection orifice was mechanically weak.

TEST #S6: This was a repeat of test S5, with extreme care taken during the test section assembly to maintain the correct orifice width. The injection was also fitted into a 19 tube bundle, with the three main target tubes pressurized to 1700 psig. The remainder were dummy tubes. Five sequential injections were made to give a total test time of 46 seconds, and an injection of 30 lbs of water. The test details and the wastage damage are given in Figure 3. It must be noted that EXTREME care was taken with this test section to ensure the injection fell symmetrically onto the two closest target tubes.

SWEAT RIG TEST

Orifice Geometry

Before Test = slit 120° x 0.008

During Test = 120° x 0.017

After Test = 120° x 0.017

Test Conditions

Injection #	H ₂ O			Na	
	Quantity mL	Time sec	Rate mL/sec	Temp (°F) Initial	Final
1	3350	10.1	332	480	
2	3300	10.3	320	780	1000
3	3100	9.2	337	800	980
TOTALS	9750 (21.5 lb)	29.6 sec	329 (0.73 lbs/sec)		

Test Results (Numbers denote maximum wastage on each tube)

FIGURE 2 WASTAGE DAMAGE FROM TEST S5

SWEAT RIG TEST

INJECTION #	H ₂ O			Temperatures (°F)		
	Quantity mL	Time Sec	Rate mL/sec	Sodium		H ₂ O Test
				Initial	Final	
1	1300	4.4	296	440	-	260
2	2700	9.7	277	550	900+	260
3	2500	9.0	278	770	970	256
4	3100	11.0	282	880	980	160
5	3650	11.9	307	825	990	136
TOTALS	13,250 (30 lb)	46 (sec)	288 (0.64 lbs/sec)			

Note:

Numbers denote
maximum wastage
on each tube.

FIGURE 3 WASTAGE DAMAGE FROM TEST S6

3.2 Velocity Profile Test Results

90° Circumferential Slit: Water was injected through the injection orifice used in test #S3. The result of an angular scan in the plane of the jet is shown in Figure 4. The injection was made with a reservoir pressure of 50 psig, the jet being injected into a container of water. An axial profile of the jet is given in Figure 5, and a diagrammatic representation in Figure 6. Note that the water jet width is only about half of the injection orifice angle, or $\sim 45^\circ$. The jet barely impinges onto the two nearest tube locations, and has a form similar to that which would be predicted from the pattern of wastage found in test #S3. Based on this data the length of the injection orifice was increased to 120° for test #S4 through #S6.

120° Circumferential Slit: The angular velocity profile in the plane of the water jet is shown in Figure 7, and the axial profile at two locations in Figure 8. The test data indicated that the water jet is injected as two streams from the end regions of the slit. A further test was made in which high pressure argon (1700 psig) was injected through the 120° slit. Small amounts of water were entrained in the gas flow, and the cooling due to rapid gas expansion caused the droplets to freeze onto the target tubes producing an ice build-up that was remarkably similar to the wastage patterns observed during tests #S5 and #S6.

3.3 Orifice Fabrication Results

A fabrication technique for forming circumferential slits in a 3/8 inch diameter tube was developed. Slit widths were regular, with about 0.0005 inch variation around the circumference. Slits with circumferential angles of 30°, 60°, 90° and 120° were fabricated successfully. Two pieces of tubing were machined, one piece having a recessed section removed to form the slit geometry. These two pieces were then welded together with a full penetration weld, except for that part of the circumference containing the slit section. Allowance for shrinkage during welding is required (approximately 0.002 inches).

Figure 4 Angular Scan in Plane of Jet From 90° Slit

Water injection into water
Reservoir pressure = 50 psig
Slit geometry = $90^\circ \times 0.016''$
Injector used in Test #S4

Figure 5 Axial Scan across Plane of Jet from 90° Slit

Figure 6 Graphical Representation of Injected Jet (90° Slit)

Injector Geometry = 120° slit x 0.017" width (used in Test S6)

Injection Pressure = 50 psig

Injection Fluids = Water-into-water

Figure 7 Angular Velocity Profiles of 120° Slit Injector

Injector Geometry = 120° slit x 0.017" width (used in Test S6)
 Injection Pressure = 50 psig
 Injection Fluids = Water-into-water

Figure 8 Vertical Profile Through Jet (120° Slit)

No difficulties were experienced with slits up to 90°. For slits with 120° circumferential length the injection tube was mechanically weak. The injector could be easily damaged during installation in the test bundle, and the orifice width changed by bending with a finger and thumb grip at each end of the tube.

4.0 DISCUSSION OF RESULTS

4.1 90° Slits

Velocity profile tests showed that the effective jet angle, with low pressure water injected into water, was only about 45°. (Figure 6) Wastage tests (#S2 and #S3) show that a 90° slit orifice produced insignificant wastage on the first row tubes, and wastage on the central second row tube. Both of these data indicate that simultaneous destruction of two or more tubes is improbable with slits having circumferential widths of less than 90°.

4.2 120° Slits

Velocity profile tests showed that the effective jet angle was about 90°, with two fairly distinct columns of water separated by ~60°. (Figure 7) If high pressure gas was injected containing atomized liquid droplets, ice patterns formed on the target tubes. These patterns are very similar to the damage profiles measured in the wastage tests (#S5 and #S6).

The wastage tests produced significant wastage on adjacent first row and second row tubes, but different penetration rates for each tube. Even when extreme care (Test S6) was taken to produce symmetry and equal wastage rates, significantly different penetration rates (~17%) were recorded. A 17% difference in penetration rates translates to about a 14 second difference in failure times for two adjacent tubes. Therefore, it is concluded that simultaneous (fraction of a second) failures of two or more tubes is highly improbable.

5.0 CONCLUSIONS FROM TEST A-4 SUPPORT TESTS

The following conclusions were drawn from the experimental program conducted in support of LLTR Series II Test A-4:

- Fabrication technique for making precise slits was developed.
- Wastage boundary agrees with velocity profile boundary.
- Circumferential slit angles would have to be 120° to ensure adequate coverage of adjacent tubes.
- 120° circumferential slit weakens tubes such that maintaining desired slit dimensions for LLTI application is not considered practical. Use of intermittent slit geometry would be required.
- 120° slits, precisely machined and precisely aligned with target tubes, produced different penetration rates on adjacent tubes.
- Production of simultaneous failures in LLTI with 120° slit or simulated interrupted slit is not considered credible.