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SODIUM-WATER REACTION ACOUSTIC NOISE

FOR LIQUID PHASE INJECTIONS

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ABSTRACT

Data on liquid and steam injections into sodium were recorded during a series of wastage experiments. These data are analyzed for acoustic power and spectral characteristics, expanding the data base up to 10 gm/sec injection rates from the earlier 0.5 gms/sec. No significant difference in acoustic power was measured between low temperature steam and liquid injections for the same mass flowrates. The bandwidth for steam injections is broader than for liquid injections. Reaction product deposition during water injections appears to cause a decrease in signal strength with test duration.

SODIUM-WATER REACTION ACOUSTIC NOISE FOR LIQUID PHASE INJECTIONS

1. INTRODUCTION

Water leaking through a small defect in an LMFBR steam generator tube reacts with sodium producing heat, corrosive products, and acoustic pressure pulses. Unless timely corrective action is taken, the leak will eventually enlarge by self damage at the injection site, and/or additional leaks will be created by impingement damage on adjacent tubes. The goal of the leak monitoring system is to detect leaks before significant increases in leak rate occur, permitting shutdown prior to activation of the rupture disc in the steam generator over-pressure protection system.

An acoustic leak detection system can detect and locate relatively small water leaks in typical LMFBR steam generators. A reference system based on array processing techniques similar to those of passive SONAR and RADAR was designed [1]. Accelerometers are fitted in a predetermined pattern to the outside surface of the vessel. Electronic circuitry selects a number of accelerometers. This array is beamformed and focussed within the vessel; and the acoustic power is measured for each predetermined focal point. The presence of a leak is indicated when a local acoustic power measurement exceeds a set threshold level.

One of the most important parameters in predicting the performance and limitations of an acoustic leak detection system is the absolute amplitude of the acoustic pressure generated by a sodium-water reaction.

The first parametric study of the acoustic signals generated by liquid water injections has been performed and is reported herein. Parametric effects of injection rate and orifice size have been measured and analyzed.

The detection capability of the acoustic leak monitoring system is very sensitive to the signal-to-noise ratio at the transducers. Small decreases in signal amplitude require significantly longer data acquisition and processing times before a leak can be reliably confirmed. Thus the character of the acoustic pressures from sodium water reactions impact strongly on the design of the digital data processor.

To provide data for design and performance predictions, measurements of acoustic pressures associated with small sodium-water reactions were made in the SONic Amplitudes Rig (SONAR). Testing, initially designed to provide wastage data, provided an opportunity to take these measurements. Liquid phase water was injected at rates varying from 1.2 gms H₂O/sec to 21.0 gms H₂O/sec into sodium; the resultant SONAR vessel wall motion was monitored by accelerometers. Prior to the tests, the SONAR vessel had been calibrated so that data were measured in absolute magnitude, rather than in relative terms [2]. Absolute measurements of sound generation allow test data to be applied to any steam generator design.

2. DESCRIPTION OF TEST EQUIPMENT

2.1 SONAR Rig

The SONAR rig (Figure 1) was designed and built in support of the acoustic leak detection/location program, and operates up to typical LMFBR operating conditions. The stainless steel pressure vessel is 44.5 cm diameter and 122 cm high. A full diameter 300 lb. class flange provides access to the vessel interior. This flange has a smaller port covered with a 15.24 cm x 300 lb. class flange to permit easier and faster access to test fixtures. Injection lines, instrumentation and other penetrations enter the vessel through these flanges. Calrod heaters are used to raise the vessel and its contents up to the design limit of 510°C (950°F). The maximum allowable working pressure is 250 psig at 510°C, but with the modified flanges, this is reduced to 150 psig at 510°C.

Figure 1. SONAR Rig

The vessel is filled from a fifty-gallon drum of sodium through a one inch (2.54 cm) line and 1/2 inch (1.27 cm) sodium valve at the bottom of the vessel. After the test sequences are completed, the sodium and dissolved reaction products are flushed back into the fifty-gallon drum. Level probes from the flange allow the vessel to be filled with sodium to a consistent height. The remaining volume is filled with argon cover gas from a pressure bottle. The vessel pressure and temperature are maintained constant by appropriate controllers.

Gas from the vessel, including gaseous reaction products, can be vented into an adjacent collection tank for subsequent controlled release. The pressure in the vessel is maintained constant by means of a pressure activated switch and solenoid valves on the 2.54 cm line connecting the SONAR vessel and the collection tank. A similar parallel line contains a rupture disc assembly to provide inherent protection should the controller fail to operate. Similarly, the collection tank has an over-pressure relief valve venting to atmosphere. All gases from the collection vessel are vented to atmosphere through a stack pipe which has a propane flame at the exit to ignite any hydrogen gas.

Water from a reservoir system can be injected under helium pressure into the SONAR vessel. This water is stored and injected cold, but is passed through a heat exchanger section submerged in the sodium so that the injected fluid is near the same temperature as the sodium. A capillary injection tube is lowered into the sodium through a compression fitting in the small flange. The opening at the end of the capillary tube is reduced in diameter to produce a 0.005 inch diameter to 0.013 inch diameter opening. This reduction in diameter is done by swaging, a process used in the wastage programs to produce small leaks [3-5]. The injector tube always points downward and is in the same elevation as a ring of accelerometers mounted on the vessel outer circumference. Located along the capillary tube where it first enters the pool of sodium is a section of 1/4 inch tubing to act as a heat exchanger. This heat exchanger allows the water to come to thermal equilibrium with the sodium before injection.

The SONAR vessel was designed and fabricated to obtain measurement of the sound level of small sodium-water reactions ($\pm$ approximately 2 grams $\text{H}_2\text{O}/\text{sec}$). Eight Bruel and Kjaer 4344 accelerometers are mounted on the circumference of the vessel at the same level as the injection orifice. Outputs from these transducers are amplified and recorded during sodium-water reaction tests and provide absolute acoustic pressure amplitude measurements. Details of the accelerometer attachment are shown in Figure 2.

2.2 Test Articles

During the test program, three test article designs were used to obtain data. The first six tests were made in a nineteen-tube bundle with the injector tube in the central location (Test Article A). Tube-to-tube separation is 1.51 cm (0.595 in.) minimum, the tubes having a triangular array pattern. Injector-to-tube spacing for the second row is 3.34 cm (1.315 in.). The injector was made by drilling through the wall of the 1.588 cm (0.625 in.) diameter x 0.277 cm (0.110 in.) wall thickness tube. The target and injector tube were fabricated from certified material. The alignment of the water jet was carefully checked to ensure it was impinging normally onto the target tube. The target tube was pressurized to 1600 psig with argon gas. Both the target and injector tube were heat treated following welding of the end fittings and prior to the test. The completed test article, prior to insertion into the shroud, is shown in Figure 3.

A second test article (Test Article B) was similar in structure to the first, the only change was to the injector tube. A stainless steel capillary tube was swaged and cut to give a reduced section length of about 0.28 cm. The reduced length was then inserted through a hole in the injector tube, and welded to the inner wall of the tube. The injection orifice was then drilled through the reduced section of the swaged tube. This technique reduced the pressure losses in the injection system and minimized self-wastage effects which occurred with Test Article A. The injector tube is shown in Figure 4.

Figure 2 Accelerometer Attachment Concept

Figure 3 TEST ARTICLE TYPE A

Figure 4 INJECTOR TUBE, TEST ARTICLE B

A simplified four-tube test article was fabricated (Test Article C). In order to minimize changes in $[L/da]$ as the target tube was penetrated, the target tubes were machined to a wall thickness of 0.051 cm (0.020 inch). The injector tube was similar to that used in Test Article B, a swaged and drilled capillary tube inserted through the normal tube wall. The test article is shown in Figure 5. The center tube could be rotated after each test to impinge the jet onto the four target tubes consecutively.

Test Article D consisted of two test assemblies held in the same structure. Swaged and drilled capillary tubes injected steam against a pressurized target tube. The angle of impingement of the jets was not normal, but struck the target tube midway between tangential and normal. The test article is shown in Figure 6.

2.3 Data Acquisition and Analysis

The eight Bruel and Kjaer 4344 accelerometers are thermally insulated from the vessel by ceramic standoffs identical to the ones used for noise measurement on EBR-II in Idaho and at Hengelo in The Netherlands [6]. The signal from the accelerometers are amplified by Tektronix AM502 amplifiers. The amplifiers bandpass the signals from 1 kHz to 30 kHz with 6 dB/octave filters. The resulting signals are analyzed in real time by a Hewlett Packard 5240A signal analyzer. These signals are also recorded on magnetic tape by a Sangamo Sabre II 14 channel tape recorder and monitored with a loud-speaker system. The leak rate is measured through the use of a differential pressure sensor. This sensor monitors the level in the water injection reservoir. The reservoir level signal is recorded on a Solten chart recorder. Figure 7 illustrates the data flow for the SONAR rig.

During a typical test, the eight accelerometers mounted on SONAR give an rms voltage proportional to the local acceleration of the vessel wall. The accelerometer sensitivities vary from about 2.5 to 2.9 millivolts per "g" acceleration. From the wall acceleration, the incident acoustic pressures can be calculated. The data are presented in absolute microbar acoustic pressure at a distance of 30 cm from the source [7]. The conversion takes

Figure 5 TEST ARTICLE, TYPE C

Figure 6 TEST ARTICLE, TYPE D

Figure 7 Experimental System to Generate Noise and Monitor Acoustic Noise

into account accelerometer gain, amplifier and tape recorder gain, the inverse distance attenuation character of signal transmission, vessel reverberation, and acceleration of the vessel wall by incident acoustic pressure.

Auto spectra amplitudes presented in this report are relative to 1 microbar acoustic pressure per root hertz. Auto correlation amplitudes presented in this report are only relative and the bandwidths are given on each auto correlation. These bandwidths were calculated based on calibration of the auto correlation with filtered white noise.

3. TEST CONDITIONS

Tests were conducted providing sixteen data points. The program consisted of four separate phases.

A) Phase 1: The first six tests experienced severe self-wastage of the injector (for orifice diameters > 0.015 in.) making data interpretation difficult. The cause of the self-wastage was excessive pressure loss prior to injection of the water. Choking of flow from the 0.043 in. capillary tube connected to the injector tube produced a low pressure chamber behind the drilled hole. The injected fluid was probably steam rather than liquid. (Test Article A, Figure 3).

B) Phase 2: The injection system was modified so that the 0.043 inch capillary tube was connected directly to the injection orifice. This reduced the self-wastage for orifice diameters above 0.015 inch. However, the injection pressure for the larger orifice sizes was still below the required 1700 psig. The water reservoir was limited to 2500 psig, and the maximum diameter of capillary tube was 0.043 inches. Due to these rig limitations, the pressure losses along the capillary tube in the SONAR vessel could not be compensated for. Changes in the limits would require SONAR rig modification. (Test Article B, Figure 4).

C) Phase 3: The Phase 2 tests allowed completion of the designed test matrix, but at a waterside pressure which was outside the test objective of 1700 psig. A third group of tests was made, therefore, with the correct waterside pressure, a maximum orifice size of 0.0135 in. (0.0343 cm), and a range of orifice-to-target distances. (Test Article C, Figure 5).

D) Phase 4: Two tests were run to show the effect of changing the flame impact angle from normal. (Test Article D, Figure 6).

A full tabular listing of all test conditions is given in Table 1 and a test matrix in Table 2.

TABLE 1

TEST CONDITIONS

<u>TEST #</u>	<u>CONDITIONS</u>
	<u>PHASE I</u>
9002	Leak size 28 mil. Nineteen tube bundle: Test Article A. First Injection: 1702 cc, 163 seconds; Mass flow ~ 10.13 gm/s. Second injection: 1210 cc, 118 seconds; Mass flow: ~ 9.1 gm/s.
9003	Leak size: 20 mil. Test Article A. Injection: 486 cc, 42s; Mass flow: ~ 10.4 gm/s.
9004	Leak size: 15 mil. Test Article A. Injection: 197 cc, 34s; Mass flow 6.3 g/s
9005	Leak size: 28 mil. Test Article A. Injection: 256 cc; 22.5s; Mass flow: 11.4 g/s
9006	Leak size: 13.5 mil. Test Article A. Injection: 328 cc, 58.4s; Mass flow: 5.6 g/x
	<u>PHASE II</u>
9007	Leak size: 28 mil. Nineteen Tube Test Bundle. Test Article B. Injection: 547 cc, 55s, Mass flow: 9.9 g/s
9008	Leak size: 20 mil. Test Article B. Injection: 306 cc, 35s. Mass flow: 8.7 g/s
9009	Leak size: 29.2 mil. Test Article B. Injection: 318 cc, 38s. Mass flow: 8.4 g/s
	<u>PHASE III*</u>
9010	Leak size: 13.5 mil. Five Tube Bundle. Test
9010R	Article C. First injection: 34 cc, 15s. Mass flow: 2.27 g/s Second injection: 15.9 cc, 3.4s. Rate: 4.7 gm/s
9011	Leak size: 13.5 mil. Test Article C. Injection One: 348 cc, 278s. Flow 1.25 g/s Second injection: 26.46 cc, 9.04s. Mass flow: 2.93 g/s

*Phase III - These tests conducted sequentially with leak rotated 90°
between tests.

TABLE 1 - Continued
TEST CONDITIONS

<u>TEST #</u>	<u>CONDITIONS</u>
9012	Leak size: 13.5 mil. Test Article C. Injection: 19.4 cc, 10.4s. Rate: 1.93 g/s
9013	Leak size: 13.5 mil. Test Article C. Injection: 253 cc, 205s. Rate: 1.24 g/s
<u>PHASE IV</u>	
9014	Leak size: 29.2 mil. Test Article D. Five injections: total H ₂ O injected: 1739 cc, 83s. Rate: 20.95 gm/s.
9015	Leak size: 13.5 mil. Test Article D. Four injections: 1593 cc, 151s. Rate: 10.5 gm/s

Table 2
Test Matrix

Test #	do mils	inch	Init. Na temp °F	Final Na temp	H ₂ O Pres- sure (psig)	Total Test Time sec	Time to failure sec	avg	Injection rate (g/s)		Time	Inject Type
									min	max		
9001	13.5	0.595	580	580	1750	85	56.5	4.3	3.8	5.1	53	A
9002	28.0	1.315	580	640	-	308		9.7	8.3	15.4	172	A
9003	20.0	0.595	580	585	-	47.6	44.6	9.8	9.4	11.5	45	A
9004	14.5	0.595	580	580	1750	38	32.8	6.3	5.8	7.7	32	A
9005	28.0	1.315	580	580	-	17	-	11.4	-	-	14	A
9006	13.5	0.595	580	580	1750	58.4	55	5.6	9.3	5.9	52	A
9007	28.0	1.315	570	620	-	55	-	9.9	9.0	10.7	52	B
9008	20.0	0.585	560	565	-	37	-	8.7	8.1	9.4	21	B
9009	29.2	0.595	560	575	-	40	-	8.4	7.6	8.6	33	B
9010	13.5	0.405	575	577	1750	17	-	2.27	-	-		C
9010R	13.5	0.405	580	578	1750	5.4	-	4.7	-	-	2	C
9011	13.5	0.648	578	578	1750	11	-	2.93	-	-	8	C
9012	13.5	0.270	570	570	1750	13	-	1.93	-	-	7	C
9013	13.5	0.879	568	572	1750	13	-	1.24	1.24	1.25		C
9014	29.2	1.315	577	665	-	83	-	21	20.6	21.4		D
9015	13.5	0.595	670	740	1750	151	-	10.5	9.6	15.3		D

4. TEST RESULTS

4.1 Effect of Water Injection Rate on Signal Character

The autospectra from the data recorded from accelerometer #1 for three different liquid flowrates are shown in Figure 8. As the injection rate is reduced there is a commensurate reduction in the acoustic power. No changes in the spectral content are noticeable as the injection rate is changed, except for higher amplitudes at high frequencies for the larger injection rates. The autocorrelations of the same signals are given in Figure 9. These confirm wider bandwidths at the larger injection rates. It should be noted that the lowest injection rate is probably from a partially plugged orifice. Higher flowrates would be expected for the orifice size which was measured prior to the test.

When the data for two very similar tests, run for approximately the same duration, are compared, the autospectra are very similar, Figure 10. However, the signal strength will change with time due to the build-up of reaction products (see section 4.3).

A plot of the acoustic power generated by the sodium-water reaction is shown in Figure 11. Power is plotted as a function of water injection rate. A wide scatter in the data is evident; the reason for this will become apparent from results and discussions. Note that the acoustic power from a liquid injection is similar to that for steam injections.

All of the data from the LLTR Series II Test A-3 support experiments[5] are plotted in Figure 11. In general, injections made through the large orifice diameters produced steam injections because of the pressure losses

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TYPICAL RESULTS

<u>Phase</u>	<u>Orifice Diameter (inch)</u>	<u>Injection Rate (gm/sec)</u>	<u>Cover Gas Pressure psia</u>	<u>Sodium Temp °F</u>	<u>Acoustic Power dB</u>
Liquid (9007)	0.0292	9.9	141	570	51
Liquid (9010)	0.0135	4.7	145	580	45
Liquid (9012)	0.0135	1.9	141	570	37

Figure 8 Effect of Water Injection Rate on Autospectra

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Figure 9 Effect of Water Injection Rate on Auto-Correlation

A SPEC 1 R# 31
A SPEC 1 R# 46

Phase	Orifice Diameter	Injection Rate (gm/sec)	Cover Gas	H ₂ O Pressure (psia)	Na Temp °F	Acoustic Power
Liquid	0.0135	5.6	145	1765	580	42.140
Liquid	0.0135	4.7	145	1765	578	44.649

Figure 10 Reproducibility of Test Data

Acoustic
Power
(db)
@
60 cm

Figure 11 Absolute Acoustic Amplitudes

along the injection line. As a result the pressure at the injection orifice was below the saturation pressure at the sodium temperature. The actual injection pressure was not measured [4].

4.2 Comparison of Liquid and Steam Injections

The plot of acoustic pressure against injection rate, Figure 11, includes both steam and liquid data. This graph shows that the acoustic power from low temperate (580°F) steam and liquid injections are similar at the same mass flowrate.

The autospectra of liquid and steam injections at the same mass flow are shown in Figure 12. Comparison of the spectra indicates that the steam injection has a broader bandwidth than that for a water injection. This is confirmed by the autocorrelation diagram for the same data, Figure 13.

A direct correlation of the acoustic power associated with different phase injections is difficult, since liquid injection acoustic power changes with time as reaction products collect at the site.

4.3 Effect of Reaction Product Deposition

During the course of the injection tests, reaction products continued to accumulate around each test article. Figures 14 through 16 show some of the accumulated reaction product build-up for the nineteen tube bundle, test article B, and the five-tube bundle test article C. The effect of this material surrounding the sodium-water reaction site was observed in comparison of the initial acoustic power spectra with those produced near the conclusion of the test.

A clear diminution of the strength of the acoustic signal is evident, Figure 17. There is a 20dB decrease in acoustic power in 300 seconds. This can also be seen by an autospectrum taken 300 seconds into the injection, Figure 18, when compared with the autospectrum of the same injection in the first few seconds, Figure 12.

Similar fluctuations in the acoustic power, in all tests of prolonged duration were noted. Typically steady decreases in signal strength were interrupted by sudden relative increases as reaction products broke away and then alternately continued to form around the site.

Figure 12 Comparison of Autospectra of Steam-vs-Liquid Injection

Figure 13 Bandwidth Comparison of Steam-vs-Liquid Injection

Figure 14 REACTION PRODUCT DEPOSITION (WATER)

Figure 15 TUBE ASSEMBLY - POST TEST - SIDE/BOTTOM VIEW

Figure 16 REACTION PRODUCT DEPOSITION (WATER INJECTION)

Figure 17 Effect of Reaction Product Deposition

Figure 18 Effect of Injected Fluid Phase (300 secs into injection)

4.4 Comparison with Previous Data

Data from a series of tests in which steam phase fluid was injected into sodium have been published [7]. A summary curve for steam injection data is reproduced in Figure 19. The current data has been summarized in Figure 11. Comparison of data is shown in Figure 20. Considering the scatter in both sets of data, and the variation of liquid phase data with time, the difference between the two data curves is not considered significant.

5. CONCLUSIONS

The major conclusions of this experimental study are as follows.

1) As both liquid and low temperature (580°F) steam injections produced similar spectra at the same mass flowrate, no significant effect of phase was noted on acoustic power.

2) A narrower bandwidth was found to be characteristic of the liquid injections.

3) An expansion of the previous liquid injection data base from 0.5 gm/sec, up to injection rates of 10 gm/sec was accomplished.

4) Decreases in signal amplitude due to solid reaction product build-up at the injection point were noted in each test.

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*Pressure = RMS Acoustic Pressure in Bandwidth of 1 kHz to 10 kHz at a distance of 30 cm from source.

Figure 19 Effect of Steam Injection Rate (RMS amplitude)

Figure 20 Steam and Liquid Injection Rate-vs-Acoustic Power

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