**Liquid Metal Engineering Center
(LMEC)
Semiannual Technical Progress Report**

January-June 1970

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Liquid Metal Engineering Center

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INTRODUCTION

The overall objective of the LMEC is to provide optimum operation and management to implement the following major functions:

- 1) Operation, maintenance, and modification of facilities designed to test and evaluate liquid metal components, and the performance evaluation of components tested.
- 2) Construction of authorized test and evaluation facilities.
- 3) Provision of training for industrial personnel in liquid metal system and component technology.
- 4) Operation of the Liquid Metals Information Center (LMIC).
- 5) Provision of engineering advice, consultation, and technical contract management to the U.S. Atomic Energy Commission (AEC) and its contractors, generally in the technical area of liquid metal component technology, with specific tasks assigned by the AEC Division of Reactor Development and Technology (RDT).
- 6) Preparation of RDT LMFBR-oriented tentative standards, and review of such standards prepared by others.
- 7) Development of a Quality Assurance program in accordance with RDT policy, implementation of this policy within LMEC, and support to RDT in implementing this policy, as directed, in RDT programs.

The immediate purpose of the LMEC is to support the LMFBR program by supplying detailed technical effort to the LMFBR development program. To accomplish this, the LMEC program is divided into technical and administrative projects according to special requirements of the LMEC and the LMFBR Program Plan. The relationship of each of these projects to the LMFBR Program Plan is indicated in the following table.

Only those projects which, during this reporting period, have generated direct technical progress information of immediate use and interest to the LMFBR community are reported herein. Those projects identified as being administrative, general support, or contractor management in scope, or which have generated limited technical information, are not included.

LMEC REFERENCE TO THE LMFBR PROGRAM PLAN

Project Subaccount No.	LMEC Project	LMFBR Program Plan Reference
12100*	AEC Assistance and Consultation	Directly or indirectly related to all tasks.
12101*	Codes and Standards	2-2.3, 3-2.2
12107*	Maintenance and Malfunction Analyses	2-1.7, 2-1.9, 3-2.1.3, 3-2.2, 3-2.4, 3-4.3
12109*	Quality Assurance	2-2.3, 3-2.3, 3-4.2, 3-4.3
12200*	LMFBR Test and Facility Engineering, Planning, Coordination, and Evaluation	3-5.1, 3-5.2, 4-1.4, 5-2, 5-3, 5-9
12300*	Liquid Metal Pump Systems	3-11
12400*	Valve Contract Management and Testing	3-8.5
12500*	LMFBR Steam Generator and Intermediate Heat Exchanger Systems and Contract Management	3-6, 3-12, 4-3
12600*	Piping Systems and Contract Management	3-4.3, 3-8.2, 3-8.3, 3-8.4, 3-8.6
12700	Sodium-Water Reaction Study	3-6.1.1, 3-6.4, 3-6.5.3
13200	Operation of Sodium Components Test Installation (SCTI)	3-5.1, 3-6.1, 3-6.5, 3-12.1, 3-12.4
13300*	Liquid Metals Information Center	All elements except Element 9
13400*	Sodium Pump Test Facility (SPTF)	3-11, 3-11.5, 3-11.5.3
14100*	Sodium Pump Seal Test Program	3-11.3.1
14200*	Sodium Pump Bearing Test Program	3-5.2, 3-11.3.2
15100	Precision Mechanisms in Sodium (PMIS)	3-3, 3-7.3, 3-10.3, 3-11
15200	Materials Compatibility in Sodium (MCIS)	5-1.6, 5-1.8
16200	Steam Generator and Intermediate Heat Exchanger Performance Evaluation	3-6, 3-12
17100	Instrumentation Testing, Evaluation, Calibration, and Standards	4-1 through 4-7
17110*	Strain Gage Development Contract Technical Management	4-7.11
17120*	Pressure Sensor Development Contract Technical Management	4-7.7
17200*	Instrumentation and Standards Laboratory	4-1.4
89110	Chemical and Metallurgical Laboratory	3-3.1, 5-5.1 through 5-5.7
89300	LCTL/SCTL Operation, Maintenance, and Modification	3-5, 3-6, 4-1
89400*	Technical Liaison for Materials and Process Development	3-3.1, 3-4
89450*	Component Materials Management and Control	3-3.2

*These projects are identified as being administrative, general support, or contractor management in scope. Since they do not generate direct technical progress information of immediate use and interest to the LMFBR community, they are not included in this technical progress report.

Highlights of LMEC achievements during this reporting period include the following:

- 1) Completed FFTF Test T-1B (grid plate and bypass flow).
- 2) Started FFTF Test T-1D on schedule.
- 3) Completed FFTF CRDM Roller Nut Test Phase I (PMIS).
- 4) Continued liquid and vapor sodium sliding wear tests in support of FFTF.
- 5) Investigated cause of Alco steam generator tube failure, coordinated with industrial contractors, effected repairs, and resumed testing to final failure. Prepared proposed post-test examination plan.
- 6) Installed SCTI full-flow demineralizer; completed preparation for installation of SCTI Data Acquisition System (DAS).
- 7) Completed two pump seal test rigs and remodifications (for PMIS).
- 8) Initiated development of semi-empirical correlations for wastage resulting from small water leaks into sodium.
- 9) Developed improved choking theory for two-phase flow in sodium-water reaction small-leak studies.
- 10) Developed welding, removal, and reinstallation technique for 900°F strain gage.

SUMMARY

SODIUM-WATER REACTION STUDY

Wastage data for 2-1/4 Cr - 1 Mo ferritic steel obtained in APDA Rig 10 tests have been analyzed in an attempt to develop data correlations on the basis of cavitation impact erosion theory. Data were analyzed on the basis of both penetration depth and volumetric metal loss. The correlations obtained so far are less than satisfactory, but do offer promise that the approach being employed is likely to be fruitful.

The computer simulation of a flashing-water jet has been extended from the one-dimensional model, discussed in the previous semiannual progress report (LMEC-70-1), to a two-dimensional planar-jet model. This permits the calculation of jet parameters in terms of axial distance from the choke plane.

OPERATION OF SODIUM COMPONENTS TEST INSTALLATION (SCTI)

Alco/BLH steam generator boiling phenomena tests were continued until development of additional tube leaks in March 1970. Test results confirmed the poor thermal performance characteristics previously established, and revealed a performance instability in various operating modes.

Maintenance activities on the steam generator were completed by plugging two defective tubes and three additional tubes with partial defects. The steam generator was also modified, by incorporation of individual tube orifices at the feedwater inlet end, to increase water-side pressure drop and reduce or eliminate possible static and/or dynamic instabilities.

During preparations for a return to test operation, large cracks were found on the lower tube sheet of the steam generator. These preclude further operation of this unit. Plans are being formulated for removal and destructive examination of the steam generator.

PRECISION MECHANISMS IN SODIUM (PMIS)

A roller-nut type control rod drive mechanism (CRDM) has been operated in a sodium vapor/argon gas environment while suspended 10 ft above a sodium pool at temperatures of 600, 800, and 1050°F. To date, the CRDM has performed the withdrawal, insertion, and scram functions satisfactorily. Several inspections of the drive were performed during the testing and significant wear

of the balls and races was observed; however, dimensional changes in the mechanism were minimal and, therefore, did not affect drive performance. Sodium vapor deposition was light in most areas of the mechanism, although deposits in some bearings prevented bearing rotation at room temperature.

During the remainder of the test program, the CRDM will be held in the withdrawn position for 6 months over a 1050°F sodium pool.

MATERIALS COMPATIBILITY IN SODIUM (MCIS)

Data obtained from screening tests of a large number of candidate materials in static and unidirectional sliding contact with sodium vapor or liquid were analyzed and summarized. A report, LMEC-70-10, "Friction and Wear Screening Tests of Materials in Sodium," was published.

Experimental work on friction and wear in direct support of FFTF (Test Request T-8, Addendum 2) was initiated and completed. A total of 25 tests were involved. Among the parameters studied were the effects of contact pressure on Types 304 and 316 stainless steel with percent cold work and temperature as variables. Other tests in this series were on couples involving Inconel 718, Hastelloy C, Stellite 1016, and Stellite 6B.

STEAM GENERATOR AND INTERMEDIATE HEAT EXCHANGER PERFORMANCE EVALUATION

The diagnostic test program has been performed. Additional tests were planned and performed in part. Preliminary evaluation of test data indicates large variations in levels of heat transfer performance. Changes in heat transfer may take place suddenly or gradually depending on the mode of changing operating conditions. Correlation was established with sodium outlet temperatures. A basic explanation of anomalous performance (film boiling, static instability, or other cause) could not be achieved. A static instability model was formulated to assist in interpreting results. A test program with tube inlet orifices was planned but could not be performed.

Additional tube leaks occurred indicating a repetitive pattern of failure. Conclusive failure analysis could not be achieved.

Operational history has been updated. The degree of hazard resulting from a steam tube rupture was defined.

INSTRUMENTATION TESTING, EVALUATION, CALIBRATION, AND STANDARDS

An evaluation was performed to determine an improved stabilization procedure for the Microdot SG420 strain gages. These gages had previously been stabilized by thermal-soaking the gage at 1100°F for a period of 16 hr. Significant changes in the apparent strain characteristics of the gage were noted during thermal soak tests at 900°F after 500 and 860 hr. The resistance change of the gage elements was used as the determining factor to establish a new time-temperature stabilization technique. Three gages were tested after stabilizing at 1200°F for 48 hr. Test results after a 500- and 1000-hr soak at 900°F indicated an improvement in gage stability.

CHEMICAL AND METALLURGICAL LABORATORY

A series of oxygen-in-sodium analyses, showing the degree of radial segregation occurring in 1/2-in.-diameter sodium sample tubes, has indicated that the major amount of oxygen is concentrated in only that small amount of sodium adjacent to the inside-diameter tube surface. A series of calculations were also performed to determine the standard deviation for oxygen-in-sodium analytical results, employing the mercury amalgamation method.

A preliminary metallurgical examination of the cracks in the Alco steam generator lower tube sheet was performed. Based on observations, it is postulated that stress corrosion was the most likely cause of failure.

LCTL/SCTL OPERATION, MAINTENANCE, AND MODIFICATION

FFTF Test T-1B was completed after 2982.3 hr of testing at steady-state conditions of 750°F sodium temperature and a test section ΔP of 140 psi. Post-test examination of the T-1-5 module revealed the presence of particulate matter and an investigation was conducted to determine the nature and extent of the particulate contamination in the LCTL sodium.

In preparation for Test T-1D, several improvements were added to the LCTL system to assure sodium cleanliness. These included a modification of the cold-trap loop to enable continuous cold trapping, addition of a sodium sample station, and addition of a sodium filter.

Test Assembly T-1D was installed, Test Phase A was completed, and Phase B (steady-state at 750°F and 140 psi ΔP) was started.

Followup inspection of the 3-in. loop corrosion revealed no significant degradation from previous examinations.

I. SODIUM-WATER REACTION STUDY

(LMFBR Program Plan 3-6.1.1, 3-6.4, 3-6.5.3)

K. L. Adler

A. INTRODUCTION

The objective of this project is to develop information on the effects of water or steam leaks in a sodium-heated steam generator and to provide guidelines for applying this knowledge in the design and operation of LMFBR systems and components. As part of this task, LMEC has been assigned the responsibility for technical management of the sodium-water reaction program at Atomics Power Development Associates (APDA), Inc. Analytical work has been started at LMEC to correlate wastage data obtained by APDA in Rig 10 tests and to investigate fundamental phenomena associated with a leakage jet, in order to define a rational approach to the interpretation of experimental data and to the design of scaled sodium-water tests and meaningful simulation experiments.

B. ANALYTICAL CORRELATION OF RIG 10 WASTAGE DATA FOR 2-1/4 CR - 1 MO FERRITIC STEEL

1. Summary

APDA Rig 10 wastage data were analyzed in an attempt to develop a correlation. Two methods of expressing wastage were considered: penetration depth and volumetric loss of metal. Both analytical forms are related to the cavitation erosion theory. The resultant correlations are crude, with much data scatter, since certain presumably important variables have not yet been evaluated. Two of these undefined variables, which probably contributed to data scatter, are jet impingement angle and jet impingement velocity. The effects of two of the most important variables, water source conditions and target material, remain almost unexplored. But it is believed that the results of this effort provide some indication of the effects of flowrates, spacing, capillary radius, and time.

2. Discussion

The wastage potential of an impinging jet from a high-pressure water source in the presence of sodium has been demonstrated repeatedly in the APDA Rig 10

studies. The basic mechanisms have not been clearly defined, but the erosive potential of the liquid droplets may be of primary importance.

The objective of this effort was to provide correlations of the Rig 10 data, for both maximum penetration depth and for the volumetric wastage. This objective has been limited to semi-empirical techniques involving physically significant parameters that were applied to a regression analysis of the data.

The data correlations were necessarily limited to the evaluation of one alloy (2-1/4 Cr - 1 Mo ferritic steel) at one water source condition (600° F and 2650 psia). These two variables undoubtedly are important, but lack of data for other alloys and water source conditions precludes evaluation of their effects. Those independent variables entering into these correlations include dimensionless target spacing (X/R), time, mass injected, capillary radius, and the dynamic yield strength of the target. Other parameters that might significantly improve the data correlations include impingement angle (not yet measured) and impingement jet velocity, which will be calculated upon completion of the axisymmetric flow program.

a. Maximum Penetration Depth

The most common expression for erosion is in terms of mass or volume of material eroded per mass of impinging fluid. The erosion rate during a period of steady erosion has been related to the impact velocity and impingement angle by the expression^(1, 2)

$$\frac{\partial m}{\partial M} = \frac{K(V \cos \phi - V_c)^n}{\cos \phi},$$

where

V = impingement velocity

ϕ = inclination angle

K, n are constants of the target material

m = mass of metal eroded

M = mass of water injected

V_c = critical velocity for erosion, a function of drop size.

The physical meaning of Pearson's equation is that erosion is in the first instance a function of the normal component of the impact velocity, and that the additional erosion due to a tangential component is accounted for by the $1/\cos \phi$ multiplier.

An energy approach to predict effects both of velocity and drop size on the erosion was based on the assumption that the volume of material removed per unit area per impact, is proportional to (or a function of) the impact energy per unit area in excess of some energy threshold per unit area characteristic of the material surface.

In a simplified form, to bring out the "threshold conditions" implicit in it, and ignoring the impingement angle, the equation can be rewritten as:⁽²⁾

$$\frac{m}{M} = K \left[V^2 \left(1 - \frac{G}{2V^2 r} \right) \right] ,$$

where

G = constant depending on fluid

r = drop radius.

G represents a "critical value" such that if $2V^2 r < G$, no erosion takes place. This critical value is reported to have proved quite successful in one or two instances in correlating drop-size effect.⁽²⁾

For a given drop radius the critical velocity is given by $V_c = \sqrt{G/2r}$. Assuming that in Rig 10 tests, the impingement angle was zero, that the impingement velocity was constant for all tests, and that the drop radius was proportional to the capillary radius, a simplified function can be obtained. These assumptions are not absolutely correct but were made to permit this preliminary analysis. This provides an effect for drop size only:

$$\frac{m}{M} = k_1 \left(1 - \frac{k_2}{\sqrt{R}} \right)^n ,$$

where R = hole radius. Heymann and Arcella⁽²⁾ consider the question as to why there should be a drop size effect at all.

The total impact area (as distinguished from target area) actually increases, since the number of drops increases as r^3 and the impact area per drop decreases as r^2 when the drop radius r is reduced. The total kinetic energy of the impinging water (which remains constant) is spread out over a greater area; therefore the energy flux per unit area is reduced.

Another factor that is very likely significant is the duration of the pressure pulse on impact; for geometrically similar drops, duration must be proportional to drop radius. Thus the impulse per unit area is smaller in the impact of a smaller drop.

For a 12% chromium stainless steel, Heymann and Arcella reported a value of $n = 2.6$. However, the penetration depth will be proportional to a fraction of the power for eroded mass, probably between $1/3$ and $1/2$. Thus for penetration depth, the exponent should be close to one for this specific alloy.

A functional form chosen for representation of the spacing effect was an approximation to an exponential decrease with spacing. This form was

$$f\left(\frac{X}{R}\right) = \left(\frac{k_3}{\frac{X}{R} + k_3}\right) .$$

The resultant analytical equation was

$$\delta = 10 \left(1 - \frac{0.042}{\sqrt{R}}\right) \left(\frac{\frac{X}{R} + 410}{\frac{X}{R} + 410}\right)^2 \left(\frac{\theta}{M}\right)^{1/2} ,$$

where

- δ = penetration depth (mils)
- R = capillary radius (in.)
- X = target spacing (in.)
- M = mass of water injected (lb)
- θ = time (sec).

The dependence on mass flowrate was determined empirically. The value of the constants and exponents were determined so as to minimize the standard deviation while maintaining integral or whole fractional exponents. Calculated and experimental values of penetration, δ , are compared in Figure 1.

b. Volumetric Wastage

Volumetric losses for Rig 10 tests through test No. 39 were measured by the Southern Research Institute. Consequently, these analyses were limited to those 2-1/4 Cr - 1 Mo target tubes with measurable wastage included in the first 39 tests.

The basic form for analysis, based on the erosion concept of Thiruvengadam,⁽³⁾ is as follows:

$$\frac{\Delta V}{A_e} = \frac{I\theta}{S_e} ,$$

where

A_e = area of erosion

θ = test duration

I = erosion intensity

S_e = erosion strength

ΔV = volume of eroded material.

Certain assumptions were made to permit simplification of the analysis. The impingement area was assumed to be proportional to the spacing. This requires that spacing be large, relative to hole size (i. e. , $X/R \gg 1$), and that jet shape be invariant (invariant back pressure for a given water source condition). Thus, the term $\Delta V/X^2$ was used as a proportional representation of the wastage rather than volume per unit area. Some error will result when X/R is not large or if the back pressure varies. Data point 35, which has the largest error, has a target spacing of only eight diameters, smaller than for the other data points.

Figure 1. Analysis of Rig 10 Wastage Data for 2-1/4 Cr - 1 Mo Steel

The erosion intensity, I , will depend upon the impact loading due to the water jet. It should be proportional to the source intensity and inversely proportional to the square of the dimensionless spacing, $(X/R)^2$. Since the source intensity was not varied greatly, it was ignored in this correlation.

The erosion strength was assumed to be proportional to the dynamic yield strength at the local target temperature. (A number of references indicate that this may be more accurately a function of the strain energy.) Figure 2 presents three postulations of the yield strength of 2-1/4 Cr - 1 Mo ferritic steel extrapolated above 1100° F. The target temperatures in these analyses were assumed to be the recorded maximums. However, the actual target temperature may differ from recorded maximums by 200 to 300° F; this approach does not consider the transient conditions leading to the recorded maximum.

The basic form for the analysis presented in Figures 3 through 6 was

$$\frac{\Delta V}{X^2} = a \left(\frac{\theta}{\left(\frac{X}{R}\right)^2 Y} \right)^n ,$$

where

Y = dynamic yield strength of material

a, n = empirical constants

Figures 3, 4, and 5 present data correlations with the postulated yield strengths shown in Figure 2. Figure 6 presents results obtained when the variation of yield strength with temperature is neglected. Although the analyses do not show clear-cut dependence on yield strength, as could be expected with the inaccurate temperatures available, there is a marginal indication that yield strengths from curves 1 and 2 of Figure 2 give the best correlations. But regardless of the assumed yield strength, an overall agreement with the cavitation theory seems clearly indicated.

Figure 7 presents a correlation, in somewhat different form, that attempts an approach to expressing results in terms of dimensionless parameters:

Figure 2. Yield Strength of Decarburized 2-1/4 Cr - 1 Mo Steel

Figure 3. Data Analysis of APDA Rig 10 Wastage Tests With 2-1/4 Cr - 1 Mo Steel (Based on Curve 1, Figure 2)

Figure 4. Data Analysis of APDA Rig 10 Wastage Tests With 2-1/4 Cr - 1 Mo Steel (Based on Curve 2, Figure 2)

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Figure 5. Data Analysis of APDA Rig 10 Wastage Tests With 2-1/4 Cr - 1 Mo Steel (Based on Curve 3, Figure 2)

Figure 6. Data Analysis of APDA Rig 10 Wastage Tests With 2-1/4 Cr - 1 Mo Steel (Constant Yield Strength)

Figure 7. Data Analysis of APDA Rig 10 Wastage Tests With 2-1/4 Cr - 1 Mo Steel (Based on Curve 1, Figure 2) (Near-Dimensionless Form)

$$\frac{\Delta V}{X^2 \theta} = a \left[\left(\frac{X}{R} \right)^2 Y \right]^n .$$

This correlation would become dimensionless upon dividing the dependent function by a characteristic velocity, and dividing the independent function by the fluid impact pressure.

C. COMPUTER SIMULATION OF WATER JET

The one-dimensional model of the "small leak" situation, described in the last semiannual report (LMEC-70-1), is capable of predicting effects of initial water conditions, nozzle friction, back pressure, and of some properties of the target material upon the water droplet impact pressure, but does not permit the inclusion of the leak-to-target spacing as an independent variable. To relieve this limitation, a computer routine for the calculation of the idealized planar expansion of a steady supersonic jet of flashing water has been developed; currently, this program must terminate if a standing oblique shock wave is discovered in the flow field. Such shocks are to be expected for relatively large expansion ratios, so appropriate provisions are being incorporated in this model for "slit-type" leaks. Another program for axisymmetric jets ("pinhole-type" leaks) is still in an earlier stage of development.

Results of the planar jet calculations are illustrated in Table 1 and the following figures. The tabulation shown in Table 1 has been chosen merely for its compactness and corresponds to the untypically high back pressure of 947 psia. (A more typical back pressure of 24 psia produces six pages of computer print-out.) The case shown is for isentropic expansion after isentropic choking from a 585° F, 2650-psig reservoir state. Only the initial wave interaction regions are printed out; the uniform and "simple wave" regions may be quite readily inferred. The column headings signify respectively: the wave numbers or "Riemann" invariants $I \equiv (\nu + \theta)/2$ and $J \equiv (\nu - \theta)/2$; the Prandtl-Meyer function or "property angle," $\nu = \int \cot \mu \, d \ln U$ (in degrees, where μ (the Mach angle) $\equiv \sin^{-1} 1/M$ (M is the Mach number, and $\ln U$ is the Napierian logarithm of the velocity)); the flow deflection θ in degrees; the coordinates X and Y (in slit widths) of the intersection of the given characteristic curves (waves); the pressure P in

TABLE 1

PRINTOUT FOR PLANAR-JET CALCULATION

CONDITIONS IN AN IDEAL SUPERSONIC PLANAR JET

I, J	NU	θ	X	Y	P	M	U
0, 0	0	0	1.2873	-.5000	1298.49	2.762	533.80
5, 0	5	5	1.3482	-.4711	1207.69	2.434	553.57
5, 5	10	0	1.4155	-.5000	1118.82	2.209	577.20
10, 0	10	10	1.4121	-.4293	1118.82	2.209	577.20
10, 5	15	5	1.4871	-.4576	1031.95	2.052	604.70
10, 10	20	0	1.5679	-.5000	947.08	1.940	636.11
15, 0	15	15	1.4778	-.3730	1031.95	2.052	604.70
15, 5	20	10	1.5619	-.3998	947.08	1.940	636.11
15, 10	25	5	1.6537	-.4414	864.51	1.862	671.45
15, 15	30	0	1.7527	-.5000	784.64	1.808	710.69
20, 0	20	20	1.5436	-.3006	947.08	1.940	636.11
20, 5	25	15	1.6385	-.3249	864.51	1.862	671.45
20, 10	30	10	1.7435	-.3644	784.64	1.808	710.69
20, 15	35	5	1.8584	-.4218	707.84	1.774	753.71
20, 20	40	0	1.9831	-.5000	634.56	1.756	800.39

SIMPLE WAVE REGION

20, 0	20	20	2.5329	0.9219	947.08	1.940	636.11
20, 5	25	15	2.7344	0.8703	864.51	1.862	671.45
15, 5	20	10	2.8831	1.0149	947.08	1.940	636.11
20, 10	30	10	2.9544	0.7876	784.64	1.808	710.69
15, 10	25	5	3.1039	0.9150	864.51	1.862	671.45
10, 10	20	0	3.3038	1.0509	947.08	1.940	636.11
20, 15	35	5	3.1911	0.6694	707.84	1.774	753.71
15, 15	30	0	3.3373	0.7769	784.64	1.808	710.69
10, 15	25	-5	3.5348	0.8931	864.51	1.862	671.45
5, 15	20	-10	3.7893	1.0075	947.08	1.940	636.11
20, 20	40	0	3.4429	0.5115	634.56	1.756	800.39
15, 20	35	-5	3.5802	0.5971	707.84	1.774	753.71
10, 20	30	-10	3.7702	0.6912	784.64	1.808	710.69
5, 20	25	-15	4.0183	0.7838	864.51	1.862	671.45
0, 20	20	-20	4.3279	0.8621	947.08	1.940	636.11

pounds per square inch absolute; the Mach number M ; and the velocity U in feet per second. Note that the Mach number may actually decrease initially in the supersonic expansion of a flashing liquid, in marked contrast to the behavior of single-phase flows.

Figures 8 and 9 show the standing wave patterns in one side of such planar jets expanding from the same choked state into regions of lower ambient pressure. The dimensionless parameter λ ($\lambda \approx 0.04 L/D$ for small capillaries) is merely a measure of the nozzle friction. Although the networks are shown for 5-degree intervals, the integrations were really accomplished with 1-degree intervals and the shock initiation points were taken as the first intersection of any pair of the 1-degree waves. Physically, a shock of the type found here eventually results when the initial expansion reflects from the free boundary of the ideal jet as a sufficiently strong compressive wave.

Figure 10 shows the effects upon the jet shape of variations in back pressure, reservoir temperature, and nozzle friction. It should be noted that all but the four lowest curves are strongly wall-influenced.

Figure 11 shows the contours of constant state; that is, of constant v or of constant $(I+J)$. The several discontinuities in derivative correspond to the boundaries of the various regions within planar jets; in axisymmetric jets, such transitions are naturally less abrupt. Note that some temperatures markedly below ambient equilibrium are to be expected.

Figure 12 displays the velocity distribution along the axis for various combinations of conditions. The level of the velocity in the local uniform region that terminates the expansion is indicated for several specific ambient pressures.

D. REFERENCES

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Figure 8. Output of Planar Program ($T_o = 585^\circ \text{F}$, $P_o = 2650 \text{ psig}$,
 $\lambda = 0$, and $P_8 = 40^\circ$, $\phi_9 > 40^\circ$; $P_B = 634.56 \text{ psia}$)

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Figure 9. Characteristics Network for a Wall-Attached Example ($T_R = 585^\circ \text{F}$, $P_R = 2650 \text{ psig}$, $\lambda = 0$, $P_B = 27.49 \text{ psia}$; $P_8 = 130^\circ$, $\phi_9 = 90^\circ$)

Figure 10. Ideal Planar Jet Boundaries ($P_R = 2650$ psig)

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Figure 11. Contours of Constant Pressure and Velocity in an Ideal Planar Jet of Flashing Water ($T_R = 585^\circ\text{F}$, $P_R = 2650\text{ psig}$, $\lambda = 0$, $P_B = 27.49\text{ psia}$)

Figure 12. Axial Velocity Distribution in Ideal Planar Jets of Flashing Water ($P_R = 2650 \text{ psig}$)

II. OPERATION OF SODIUM COMPONENTS TEST INSTALLATION (SCTI)

(LMFBR Program Plan 3-5.1, 3-6.1, 3-6.5, 3-12.1, 3-12.4)
W.S. DeBear

A. INTRODUCTION

The primary objective of this project is to provide and operate a test facility for testing advanced prototype sodium-heated steam generators under simulated LMFBR operating conditions.

B. PLANT OPERATION, TESTING, AND MAINTENANCE

1. Operations and Maintenance Summary

Steaming operations, initiated in December 1969 following repairs to the Alco/BLH steam generator and the primary sodium pump, continued through the end of February 1970. These operations encompassed a comprehensive series of boiling phenomena tests designed to investigate the poor performance of the Alco/BLH steam generator as delineated in LMEC-70-1, Semiannual Technical Progress Report. The tests were designed to establish steam generator performance at various conditions of power, flow, and temperature and to determine the maximum power capability of the unit at design conditions.

At the end of February, while setting up a test point for the diagnostic test program, a "flip" (see next section, Boiling Phenomena Testing) occurred, which resulted in a rapid decrease in steam outlet temperature. This temperature change (162°F) occurred over a period of approximately 5 min. As a result of the transient, a leak developed across the steam generator outlet flange gasket. The plant was shut down and the gasket was replaced. Steaming operation was resumed on March 9, 1970, but was terminated after approximately 36 hr when evidence of water vapor was found in the cover gas over the sodium. Leakage was confirmed and the water side of the steam generator was opened to permit detailed inspection. Five defective tubes were found. Liquid penetration inspections of the upper tube sheet fillet welds also revealed a number of porosity and crack indications. All defective tubes were plugged and porosity and crack indications repaired. Individual tube orifices were installed at the feedwater inlet end of the steam generator to reduce water-side flow

maldistribution and possible static and/or dynamic instabilities, which many analysts consider to be the primary cause of the poor performance and unstable behavior. A second diagnostic test series was prepared to investigate the performance of the steam generator with orifices and to permit comparison with test results obtained in the unorificed condition. Repairs and modifications to the steam generator were completed during May, and manway closure diaphragms and covers were installed preparatory to hydrostatic testing. During the initial stages of the hydrostatic test, on May 20, 1970, water leakage was observed in the region of the lower tube sheet. The steam generator was drained and insulation removed, revealing large cracks in the lower tube sheet. Deposits of sodium oxide were noted in several regions as well as evidence of past water leakage. The decision was made to remove the Alco/BLH steam generator for destructive examination. Subsequent activity was devoted to preparation of plans and procedures for removal and examination.

2. Boiling Phenomena Testing

A series of diagnostic tests was conducted to evaluate the anomalous performance of the Alco/BLH steam generator at intermediate power levels and to determine its maximum power level at design steam conditions (2200 psig/1050°F, with 1175°F sodium inlet temperature). The first of five test series was designed to investigate the effect of sodium-feedwater ΔT on boiling phenomena by successively lowering the sodium inlet-to-outlet temperature differential while holding steam conditions and power level constant. The second series of tests maintained steam outlet temperature constant (700°F) while increasing feedwater flow and power level. The sodium-feedwater ΔT was maintained as low as possible by maximizing sodium flow and increasing the sodium inlet-to-outlet temperature differential, as required, for each power level. This group of tests provided information on the effect of increased feedwater flow and water-side pressure drop. The third test series established the maximum capability of the steam generator. The fourth series consisted of the four tests of the first group performed in reverse order to establish whether or not heat transfer characteristics were dependent on the direction of change in the sodium-to-water temperature differential at the superheat end of the boiling regime. The final test series was designed to investigate performance at intermediate power levels.

The data obtained during these tests confirmed the poor performance previously exhibited by the steam generator. The maximum capability of the steam generator was established to be between 40 and 45% of rated capacity (30 Mwt) at design steam conditions. The maximum power output (22 Mwt) was achieved with 2200 psig/700°F steam conditions during the second test series.

During several of the tests, the steam generator exhibited an unexpected and sudden shift in performance which has been designated as a "flip." This was characterized by a rapid drop of from 50 to 180°F in steam outlet temperature, with a corresponding increase of 15 to 50°F in the secondary sodium outlet temperature. These disturbances occurred as a consequence of very minor adjustments to various of the process variables, including feedwater flowrate, sodium flowrate, and steam generator sodium outlet temperature. A detailed discussion of the flip occurrences, and of overall steam generator performance, is contained in Section V, Steam Generator and Internal Heat Exchanger Performance Evaluation.

Details of the testing program are indicated in Table 2. Target conditions are indicated as well as conditions actually achieved during each test. Several of the tests originally scheduled (e.g., Tests 11, 13, and 14) are not included since the steam generator performance was such that the required conditions could not be achieved.

3. Steam Generator Sodium Level Control

Difficulty was experienced with control of the steam generator sodium level early in February. Performance of the level control system degraded to the point that it became necessary to terminate automatic operation and maintain manual control. These problems were attributed to plugging of the vapor trap through which argon is supplied to, and vented from, the cover-gas region of the steam generator. Similar plugging was evident in the second vapor trap through which cover gas is drawn for the gas chromatograph. Repeated unsuccessful attempts were made to heat and blow down both vapor traps. During a plant shutdown, both vapor traps were removed from the steam generator, steam-cleaned, and reinstalled. (Considerable plugging was evident at the inlet screens prior to cleaning.) Some improvement following cleaning of the

TABLE 2

ALCO/BLH STEAM GENERATOR BOILING PHENOMENA TEST CONDITIONS
(Sheet 1 of 5)

Test		Feedwater Flow (lb/hr)			Feedwater Temperature (°F)	Steam Outlet Temperature (°F)			Steam Pressure (psig)	Steam Generator Sodium ΔT (°F)		Steam Generator Sodium Inlet Temperature (°F)		Additional Remarks
No.	Date and Time	Target	Actual	Comments		Target	Actual	Comments		Target	Actual	Actual	Comments	
1	12-31-69 1500 to 1600	46,900	43,457 to 45,940	Fluctuated throughout test	590 594	700	689 720	Temperature changes random	2170 – 2200	275	310 316	940 946		Oscillations in steam pressure appear to be reflected in feedwater flow
2	1-1-70 1200 to 1300	46,900	45,319 to 45,940	Higher flow for last 15 min of test	599 601	700	703 709	Fluctuated through test	2180 – 2200	200	197 200	840 842		Steam pressure fluctuated within range noted
3	1-1-70 2100 to 2200	46,900	43,457 to 45,443	Oscillated throughout test	599 601	700	695 700	Circular chart trace steady	2170 – 2210	150	157 161	799 800		Steam pressure oscillation persists
3A	1-9-70 1525 to 1625	46,900	44,698		595 598	700	698 710	Two slow cycles during test	2205 2200		92 96	768 772	Slow drop from higher to lower temperatures during test	Steam pressure decreased from higher to lower value during test
5A	1-10-70 1400 to 1500		27,190 to 27,818	Oscillation plus slow cycle	592 593	700	699 702	Slight oscillation first 30 min	2200		160 163	829 830		
1	Repeat 1-19-70 2245 to 2345	46,900	47,554 to 48,796	Fluctuated during first 25 min	596 598	700	705 711	Steady rise during test	2170 2190	275	278 282	908 912	In phase with steam temperature rise	Steam pressure fluctuations occurred at same time as feedwater flow ripples
			48,423	Steady 35 min										
2	Repeat 1-20-70 0400 to 0500	46,900	47,430 to 48,547	Fluctuated throughout test	602 605	700	699 701		2190 2200	200	194 200	842 845		Steam pressure unsteady
5A	Repeat 1-21-70 1010 to 1110		76,981 to 77,353	Trace showed ripple throughout test	600 603	700	695 700	Lower temperature during first 15 min	2200	158	162 166	830 834	Lower temperature during first 15 min	Steam pressure steady

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TABLE 2

ALCO/BLH STEAM GENERATOR BOILING PHENOMENA TEST CONDITIONS
(Sheet 2 of 5)

Test		Feedwater Flow (lb/hr)			Feedwater Temperature (°F)	Steam Outlet Temperature (°F)			Steam Pressure (psig)	Steam Generator Sodium ΔT (°F)		Steam Generator Sodium Inlet Temperature (°F)		Additional Remarks
No.	Date and Time	Target	Actual	Comments		Target	Actual	Comments		Target	Actual	Actual	Comments	
5B	1-21-70 1635 to 1735		90,887 to 91,632	Slight ripple in trace	599 601	700	692 698		2190		191 198	861 866		
5A	Repeat #2 1-28-70 0210 to 0310		76,981 to 77,850	Trace oscillated during test	597 603	700	700 709	Higher temperature during last 30 min	2200	158	155 160	824 831		
6A	1-28-70 1347 to 1447		99,330 100,572	Fluctuating during test	605 - 610		708 - 712	Higher temperature during mid-test	2180 - 2200	203	203 - 206	882 - 885		
6B	1-28-70 1920 to 2020		114,229 114,974	Oscillating trace	600 - 602		707-709 700-705	High temperatures during first 15 min	2195, 2200		232 - 237	911 - 914		Steam pressure slowly rose during test
7A	1-28-70 2305 to 0005		124,163 124,783	Oscillating trace	600 - 602		700 - 706		2190 - 2200	263	257 - 262	934 - 939		Steam pressure oscillating first 30 min. Steady last 30 min.
8	2-6-70 1345 to 1445	23,400	23,590 22,721	Flow drifted down in last 30 min	600 - 604	1050	1039 - 1052	Followed path of inlet sodium temperature	2180 - 2200	400	390 - 407	1052 1068	Increased for 20 min, then drifted down till last 15 min. Drop in inlet temperature upset ΔT .	Steam pressure oscillated throughout run
8A	2-7-70 0730 to 0830		28,805	Constant	603 - 609		1042 - 1051	Lower during last half of test	2170 - 2200		466 - 471	1100 - 1106	1100 - 1102 last 40 min	Steam pressure slightly unsteady
9	2-8-70 0224 to 0324	29,200	28,557		609 - 612	1050	1035 - 1042	Lower during last 40 min	2200	400	398 - 402	1091 - 1096		

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TABLE 2

ALCO/BLH STEAM GENERATOR BOILING PHENOMENA TEST CONDITIONS
(Sheet 3 of 5)

Test		Feedwater Flow (lb/hr)			Feedwater Temperature (°F)	Steam Outlet Temperature (°F)			Steam Pressure (psig)	Steam Generator Sodium ΔT (°F)		Steam Generator Sodium Inlet Temperature (°F)		Additional Remarks
No.	Date and Time	Target	Actual	Comments		Target	Actual	Comments		Target	Actual	Actual	Comments	
10A	2-9-70 1045 to 1145		34,765 35,262	Oscillating trace	594 – 603		1048 – 1059	Circular chart trace showed 5°F lower during last 30 min	2200 – 2215		444 – 454	1141 – 1147		Steam pressure oscillating
10B	2-9-70 1300 to 1400		34,765		598 – 602		1048 – 1058		2200 – 2210	400	403 – 408	1132 – 1140		Steam pressure oscillating with steady feedwater flow
8	Repeat 2-17-70 2214 to 2314	23,400	22,721		599 – 602	1050	1049 – 1052			400	395 – 399	1067 – 1069		No steam pressure trace during test run
9	Repeat 2-18-70 0545 to 0645	29,200	29,178 29,426	Increased during test	599 – 600	1050	1042 to 1046		2200	400	396 – 398	1117 – 1120	One degree variation during first 45 min	
10B	Repeat 2-18-70 1430 to 1530		37,248		599 – 601		1048 – 1059	High temperature during last 10 min	2200	400	396 – 400	1147 – 1150		
12	2-19-70 0330 to 0430	46,900	46,561		601 – 603	1050	1050 – 1060	High temperature for 15 min during middle of test	2200	400	399 – 404	1178 – 1181		
12A	2-20-70 0900 to 1000		47,181 46,933	Lower flow during last 30 min	598 – 600		1039 – 1055	Higher temperatures during last 30 min	2200		419 – 427	1179 – 1190	Higher temperatures during last 30 min	
15A	2-24-70 0740 to 0840		47,181 46,933	Lower flow during last 15 min	599 – 602		698 – 700		2200		87 – 97	765 – 769		

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TABLE 2

ALCO/BLH STEAM GENERATOR BOILING PHENOMENA TEST CONDITIONS
(Sheet 4 of 5)

Test		Feedwater Flow (lb/hr)			Feedwater Temperature (°F)	Steam Outlet Temperature (°F)			Steam Pressure (psig)	Steam Generator Sodium ΔT (°F)		Steam Generator Sodium Inlet Temperature (°F)		Additional Remarks
No.	Date and Time	Target	Actual	Comments		Target	Actual	Comments		Target	Actual	Actual	Comments	
15	2-24-70 1145 to 1245	46,900	47,181		598 – 602	700	698 – 700	Lower temperature during last 15 min	2190	75	83 – 86	761 – 763		Steam pressure had slight oscillation
15B	2-24-70 2300 to 2400		44,698		600 – 602		698 – 702	High temperature last 10 min	2200		75 – 80	819 – 823		
16	2-25-70 0655 to 0755	46,900	44,698		599 – 602	700	695 – 702	Low temperature during last 5 min of test	2200	150	149 – 150	800 – 804		
17	2-25-70 1055 to 1155	46,900	44,698		594 – 599	700	708 – 712	Higher dur- ing last 30 min	2200	200	197 200	839 – 842		
18	2-25-70 1524 to 1624	46,900	44,698		594 – 599	700	698 – 700		2190	275	272 – 275	900 – 903	Lower during last 30 min	S.G. Sodium level control on manual range 47% to 74%
19	2-25-70 2250 to 2350	47,000	47,181		599 601	650	649 651		2200		820 822	700 704	Temperature decreased during test	
20	2-26-70 0335 to 0435	47,000	47,181	Average value oscil- lation of ± 1 div. equal to ± 124 lb/hr	599 600	650	647 650		2200	875	871 877	770 – 776	High temperature during initial 15 mins	
21	2-26-70 1125 to 1225	47,000	47,181	First 30 min	598 600	650	647 648		2200	950	949 951	858 862	Constant first 30 min, steady decrease to low value last 30 min	
			47,554	Last 30 min										

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TABLE 2

ALCO/BLH STEAM GENERATOR BOILING PHENOMENA TEST CONDITIONS
(Sheet 5 of 5)

Test		Feedwater Flow (lb/hr)			Feedwater Temperature (°F)	Steam Outlet Temperature (°F)			Steam Pressure (psig)	Steam Generator Sodium ΔT (°F)		Steam Generator Sodium Inlet Temperature (°F)		Additional Remarks
No.	Date and Time	Target	Actual	Comments		Target	Actual	Comments		Target	Actual	Actual	Comments	
22	2-26-70 2315 to 0015	47,000	46,933 47,181	15 min 45 min	600 601	650	648 652	Higher temperature during first 25 min	2200	1025	1028 1030	952 962		
23	2-27-70 0525 to 0625	47,000	46,561		602 606	650	649 653	Higher temperature during last 30 min	2200	1100	1098 1102	1024 1032	Rise in 15 min to 1029, con- stant 35 min, rise last 10 min	

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vapor traps but subsequent operation was not satisfactory for a return to automatic level control. Both vapor traps, the freeze trap, and associated vent system piping were removed from the steam generator during the next shutdown to permit additional cleaning of vent piping back to the steam generator. Following removal of the freeze trap a small amount of dilute caustic was noted in the vent piping in the area of separation. Although this finding was unexpected, it was attributed to the fact that removal had taken place during a period of extremely high relative humidity. Massive deposits were removed from each of the vent lines adjacent to the steam generator and from the penetration into the steam generator shell. Sufficient blockage of the cross-sectional area had occurred to cause gas flow restriction and the level control difficulties experienced during previous operating periods. Laboratory analyses of the deposit material showed that major constituents were Na_2O and NaOH .

4. Hydrogen Monitoring and Leak Detection

Hydrogen levels, as measured by the chromatograph monitoring steam generator cover gas, remained high during initial test operation. This was anticipated from dissociation of reaction products remaining in the steam generator from the water leak of June 1969. Hydrogen level was directly affected by system perturbations, and particularly by sodium temperature change at the low temperature end of the steam generator. The dependence was attributed to dissociation of reaction products trapped in the thermal baffle region above the lower tube sheet. (With the exception of these changes associated with variation of process parameters, no unusual increase in hydrogen level was experienced throughout the testing interval.) Although some reduction was noted during the first test series (at relatively low sodium temperatures), significant increases occurred during subsequent, high-power testing at elevated temperature. To protect against the possibility that the high hydrogen background was masking additional leakage, leak checks were performed on the steam generator during plant outages by pressurizing the water side with helium and monitoring the secondary sodium side. No leakage was detected during these tests. Hydrogen levels remained high during the second test series, with levels of 4,000 to 10,000 ppm being common. Cleanup of the secondary sodium system proceeded slowly and no trend was established indicative of eventual

cleanup. Plugging meter determinations on the secondary sodium system remained high (generally in excess of 400°F). However, laboratory analyses of sodium samples indicated that oxygen level had been reduced to 5 to 10 ppm as a consequence of the extensive cold trap operation.

On March 6, 1970, after completion of maintenance activities initiated at the end of February, feedwater flow through the steam generator bypass was established for water purification. Following steam generator preheat, sodium filling was started on the morning of March 8, 1970. All applicable instrumentation was observed for evidence of water leakage into the shell side of the steam generator. All indices were normal and startup operation was continued. Steaming operation resumed at 0447 hours on March 9, 1970. In view of the earlier observation of moisture in the freeze trap line, instrumentation was provided for periodic monitoring of the dewpoint of the cover gas over the sodium surface. Initial readings were in the -40 to -50°F range, but these increased with continued operation. Immediately before shutdown, a final dewpoint determination of +43°F was obtained. Throughout this interval, dewpoint determinations from vapor trap No. 4 remained between -60 and -70°F. (This trap is approximately 120 deg removed from the leak source as finally identified.) No unusual perturbations of hydrogen level were recorded on the chromatograph during this final interval. Following the observations of high cover-gas humidity, and the visual detection of water vapor in gas vented through the freeze trap, a manual shutdown was initiated to permit detailed investigation of the steam generator condition. An immediate helium leak check was performed after the shutdown. Definite leak indications were obtained.

5. Steam Generator Tube Leaks

Both manway covers were removed from the steam generator following the March 10, 1970 shutdown. Visual inspections, liquid-penetrant examinations, and photographic studies were made of the manway flange diaphragms prior to their removal. Both diaphragms were found to be in excellent condition with seal welds intact, and no evidence of buckling or significant distortion (see Figures 13 and 14). The diaphragms were then removed and inspections were extended to the steam and feedwater chests and to the diaphragm seating surface of the manway flanges. The as-found condition of the steam chest is illustrated

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Figure 13. Upper Manway Diaphragm - Seal Weld Closeup

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Figure 14. Upper Manway Diaphragm

in Figure 15. No unusual indications were found during these early inspections. Subsequently, detailed examinations of individual tubes and tube-to-tube-sheet fillet welds were performed to establish the actual area of leakage and to search for other defects. Two leaking tubes (3-52 and 3-53) were identified by helium leak-detection techniques. These locations are indicated in Figure 16. Following this identification, the leak-detection activities were extended to establish the axial location of the defects. Both were found approximately 1-3/4 in. below the tops of the tubes, which places the defects approximately 1-1/4 in. below the upper surface of the tube sheet. All other tubes were found to be intact, but action was initiated to obtain the services of Southwest Research Institute (SRI) to perform eddy-current testing for defects which had not completely penetrated the tube wall. In addition to the inspections described above, borescopic studies were carried out using a fiber optics borescope. Liquid penetrant techniques were used in conjunction with the borescopic equipment for improved detection of internal defects. Representative results are illustrated in Figures 17 and 18. The dye indications which are visible in these photographs are at a depth of approximately 2 in. as opposed to the 1-3/4 in. finding from the helium leak-detection studies. Consequently, it was not definitely established that the indications photographed are actually the tube defects which communicate with the sodium system.

Subsequent eddy-current inspections performed by Southwest Research Institute (SRI) confirmed abnormalities in Tubes 3-52 and 3-53. These inspections also revealed three additional tubes with imperfections of significant magnitude on their outer surfaces. Information on the defective tube is tabulated (on the following page).

The SRI inspections included all tubes to a depth of 16 in. at both upper and lower tube sheets, except for a few tubes in which excessive weld rollover prevented probe insertion. More extensive testing was carried out around all plugged tubes and around those which had leaked. No other defects were identified. The SRI studies also included review of eddy-current traces obtained after the tube leak in June 1969. None of the identified defects were evident at the time of the earlier survey.

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Figure 15. Steam Chest and Outlet Nozzle

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Figure 16. Upper Tube Sheet Diagram Showing Orientation of Defective Tubes (Initial Survey)

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Figure 17. Borescope View of Tube 3-53
(10 O'clock Position)