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PRATT & WHITNEY AIRCRAFT

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TO: Mr. A. I. Chalfant

FXM-3915

December 16, 1958

FROM: C. E. Coyle

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circ: C. E. Holtsinger, C. E. Beardsley, R. N. Wallace

SUBJECT: Type 316 Stainless Steel Inpile Forced Convection Liquid Metal Corrosion Tests; NSSA-1A1, NSSA-2A2, NSSB-1A1, and NSSB-3A3

SPECIAL REREVIEW FINAL DETERMINATION	Reviewers	Class.	Date
Class: U	HFC2	U	12-4-81
	DBW	U	12-15-81

~~Confidential RD~~	A I Chalfant	12/30/58
Classification	Authorized Classifier	Date

Abstract

NaK was pumped through four test loops constructed of type 316 stainless steel to determine the ability of the stainless steel to resist corrosion with NaK at test conditions similar to those of the Pratt & Whitney Aircraft Forced Convection Liquid Metal Inpile Loop (PW-19). The four loops, which contained heater and cooler sections so that temperature gradients could be established in the NaK circuit, operated at maximum NaK temperatures of 1660F and minimum temperatures of 1530F.

The maximum corrosion attack in the four loops, which occurred as sub-surface voiding, ranged from 0.8 to 1.5 mils except for a local area downstream of the expansion tank tee in the hot isothermal zone of loop NSSB-1A1 where it was 4.0 mils. Maximum deposits (mass transfer) ranged from none in loop NSSB-3A3 to 4.5 mils in depth in loop NSSA-2A2. From the standpoint of corrosion resistance, type 316 stainless steel appears to be a satisfactory container material for NaK at the test conditions of these loops. Neither the corrosion attack nor the mass transfer deposits had any measureable effect on the heat transfer characteristics or NaK flow rate of the loops.

Object and Scope of Investigation

The purpose of these tests was to determine the resistance of type 316 stainless steel to corrosion attack by NaK when tested at temperatures and NaK velocities, in loops incorporating features such as, fuel element to cooler wetted area ratio, gamma and neutron heated area to cooler wetted area ratio, etc., which were similar to those of the Pratt and Whitney Aircraft Forced Convection Liquid Metal Inpile Loop (PW-19).

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Object and Scope of Investigation (Continued)

In addition, the degreasing and flushing, inert gas purging, and NaK purification and sampling techniques employed in the preparation of the loops prior to testing was to duplicate as closely as possible those techniques planned for the inpile loops.

This report pertains to four tests conducted in monometallic type 316 stainless steel loops in which the NaK was heated to 1660F in the heater sections and cooled to 1530F in the cooler sections. Test loops NSSA-1A1 and NSSA-2A2, ~~which were converted from available lithium loops~~, were to duplicate only the temperatures of the inpile loops. Test loops NSSB-1A1 and NSSB-3A3 were designed and built specifically for these tests to duplicate the NaK velocities and wetted area ratios as well as the temperatures of the inpile loops.

Test Item

Loops NSSA-1A1 and NSSA-2A2 were fabricated to P&WA drawing FSK 6748, which is shown schematically in Figure 1, and were construction units 4156-U-141 and 4156-U-142, respectively. Loops NSSB-1A1 and NSSB-3A3 were fabricated to P&WA drawing TL 100437 which is shown schematically in Figure 2, and were construction units 4156-U-228 and 4219-U-22, respectively. All parts of the four loops that came in contact with the NaK were constructed of type 316 stainless steel. ~~As mentioned previously, the NSSA-type loops were on hand, having been originally constructed as lithium corrosion loops. These loops differed considerably from the NSSB-type loops which were designed specifically for these tests.~~ The differences between the two types of loops were as follows: (1) the NSSA-type loop incorporated two jacketed, finned coolers connected in series while the NSSB design had a single, unfinned, spirally wound cooler tube, (2) the NSSA loop employed a single electromagnetic pump cell while the NSSB loop employed two cells to overcome the increased NaK pressure drop due to the greater overall tubing lengths, and (3) the NSSA loop had a single heater leg whereas the NSSB loop had two separate heater legs separated by an isothermal section. The two heater legs of the NSSB-type loops were designed such that the first heater duplicated the cooler to fuel element area ratio as well as the NaK temperature rise through the fuel elements. The isothermal section was required to give accurate data on the NaK temperature out of the "fuel element" heater leg and into the "gamma and neutron" heater leg. The second heater leg provided the NaK temperature differentials and area ratios of the stainless steel sections of the inpile loops receiving gamma and neutron heating.

Each of the four loops incorporated the following sections and components: (1) a heater section in which the NaK was resistance heated by passing an electric current through both the tube wall and the NaK, (2) a cooler section in which compressed air was passed over the cooler tubes, (3) an ex-

[redacted]

Test Item (Continued)

pansion tank containing liquid metal level indicating probes fitted with special inert gas chambers around the outside of the tops of the probes (shown only in Figure 2) in which argon could be maintained at the same pressure as the inside of the tank to eliminate any possibility of leakage around the ceramic insulators, and inert gas connections, (4) a sump tank containing liquid metal level indicating probes, inert gas connections, a Fulton-Sylphon liquid metal shutoff valve, and a tube containing a Jamesbury ball valve through which NaK samples could be taken (5) a permanent magnet type liquid metal flowmeter, and (6) four-pass electromagnetic pump cells for use with the General Electric type electromagnetic pumps described under "Test Equipment".

Although not initially an integral part of the test loop itself, other test items required were (1) approximately 50 thermocouples (chromel-alumel) condenser-discharge welded to the loop at regular intervals, (2) 110-volt calrods of 200, 500, and 700 watt ratings for preheating the loop and maintaining test temperatures on the loop connecting tube sections, and (3) sufficient bulk Fiberfrax insulation to cover the entire heated sections of the loop to a minimum depth of two inches.

A listing of the pertinent dimensions of each type of loop is contained below in Table I.

TABLE I

Dimensions of Type NSSA and NSSB Loops

		NSSA	NSSB
Heater Leg I.D.		0.126 in.	0.190 in.
Effective Heater Leg Length:	First Heater	31.0 in.	9.1 in.
	Second Heater	----	51.0 in.
Cooler Leg I.D.		0.206 in.	0.338 in.
Cooler to Heater Wetted Area Ratio:	First Heater	2.3:1	9.86:1
	Second Heater	----	1.75:1
Tube Wall to NaK Heating Ratio:	First Heater	2.63:1	0.84:1
	Second Heater	----	2.11:1

Test Equipment

Although the control panels, test stands, and test stand equipment varied slightly for each of the four tests described in this report, the items listed below as well as the completely installed loop shown in Figure 3 and the control panel shown in Figure 4 are typical of all the tests:

1. The rectangular loop mounting frame conformed to P&WA drawing CLR-10088-1 and contained all the inert gas, cooling air, and electrical connections as well as a number of flexible cables running over pulleys and hung with counterweights for suspending the loop.

2. The electrical and inert gas systems conformed to P&WA drawing CLR-10088-3-5. The control panel conformed to P&WA drawing CLR-10088-4 and contained sufficient temperature recording and indicating instruments, electrical power indicating instruments, water-filled U-tubes, pressure gauges, etc. to calculate and/or monitor the desired test conditions.

3. Power for the resistance type heater sections was supplied from an 80 KVA 480/30 volt transformer (Hevi-Duty Transformer, Type T-17159-8). Power control for the transformer was accomplished with a remote operated 12 gang powerstat (Superior Electric Powerstat, Model 522098 B), rated at 168 amperes at 480 volts.

4. Auxiliary heating of the loop during preheat and heating of the connecting tubing in the loop during test was accomplished with 110-volt calrods controlled by percentage timers.

5. To remove oxygen and nitrogen from the cover gas to the loop, the argon was first passed through a NaK bubbler (P&WA drawing FSK-7758) in which the NaK temperature was held at a constant 400F and then passed through a titanium chip purifying chamber (P&WA drawing FSK-7515) in which the titanium chips were held at 1600F.

6. A manually operated powerstat (Superior Electric Powerstat, Model 1256) rated at 28 amperes at 230 volts controlled the power to the General Electric electromagnetic pump.

7. General Electric electromagnetic pumps (Catalog No. 173D644G) with a maximum rating of 30 amperes at 230 volts.

Test Prodedure

During fabrication of the loop components, trichloroethylene was used to remove residual greases and oil, and the completed loops were given an acetone flush. Loop NSSB-1A1 was given additional flushes as follows prior to evacuation and purging of the loop because of suspected oil contamination from a defective titanium-chip purifier: (1) three complete flushes with pure naptha, (2) one flush with distilled acetone, (3) one flush with pure ethyl alcohol, and (4) several flushes with distilled water.

Test Procedure (Continued)

After suspension in the test stands and after all pump, flowmeter, thermocouple, electrical, etc., connections had been made, each loop was heated to approximately 300F and purged throughout with argon from both the sump and expansion tanks by opening all fill and drain line caps and level indicating probe adapters. All fittings were then tightened, the loops were evacuated with a vacuum pump to 5 to 10 microns, and the complete loops and all inert gas piping were checked for leaks using a mass spectrometer type helium leak detector. Following this operation, each loop was filled with unpurified argon, re-evacuated to 5 to 10 microns, and refilled with argon that had been passed through the NaK bubblers containing NaK at 400F and passed over the 1600F titanium chips in the purifying chambers.

The NaK used to fill the loops was taken from a point several inches below the surface of the NaK in a 35 gallon barrel that had been allowed to stand undisturbed for approximately two days prior to the transfer to settle out as much of the heavier oxides as possible. All of the NaK used in the test loops as well as the bubblers was NaK 44. The NaK was transferred from the barrel to the sump tank of each loop at room temperature by passing it through two 20 micron micro-metallic filters in series. It was then heated in the sump tank to 700F and a number of samples were taken for chemical analysis. Between the above-mentioned sampling and the filling of the loop, the NaK was cooled to room temperature. When the loop and the NaK were preheated to 250F, the NaK was raised into the loop until the desired liquid level had been attained in the loop proper at which time the Fulton-Sylphon valve between the loop and the sump (refer to Figures 1 and 2) was closed. After the loop was filled and the drain valved closed, the NaK remaining in the sump tank was heated to 1530F, held at that temperature for two hours, and then completely removed from the tank. This procedure was followed to obtain a sump tank cleaned of any contaminants soluble in 1530F NaK prior to the sampling of the NaK drained from the loop into the sump at the completion of the test run. The loop was then gradually heated to 1530F while circulating the NaK slowly at isothermal conditions prior to increasing the flow rate as the 130F temperature gradient was established. Test conditions were maintained by regulating the NaK flow rate with the electromagnetic pump, the heat input to the heater leg, and the amount of cooling air to the cooler leg. Test conditions with respect to the cooler heat fluxes were calculated from a heat balance of the cooler (See Appendix A for sample calculations) as well as from thermocouple and flowmeter data.

Termination of test NSSA-2A2 was effected by gradually bringing the loop to 1530F isothermal flow conditions before dumping the NaK from the loop into the sump tank where it was sampled at 1530F. The remaining three test loops were dumped immediately upon discover of the leaks and no posttest NaK samples were taken.

Test Results

The NSSA-type loops were each tested at the same test temperatures as the NSSB-type loops but velocities and heat fluxes were different. The test conditions for each type of loop are outlined below in Table II.

Table II - Test Conditions of Loops Type NSSA and NSSB

		NSSA	NSSB
NaK Temperature into First Heater, °F		1530	1530
NaK Temperature into Second Heater, °F		--	1630
NaK Temperature out of Heaters, °F		1660	1660
NaK Temperature into Cooler, °F		1660	1660
Temperature Gradient through Cooler, °F		130	130
Cooler Fluid Velocity, fps		6.5	11
Heater Fluid Velocity, fps		19	35
Heater Tube Wall to NaK Heating Ratio:	1st htr.	2.63:1	0.84:1
	2nd htr.	--	2.11:1
Cooler Heat Flux, BTU/hr-ft^2		43,500	98,300

Loop NSSA-1A1 operated for 96 hours before a leak in the pump cell caused temporary interruption of the test. The loop was completely decontaminated, a new pump cell was installed, and the same startup procedure as outlined above under "Test Procedure" was followed until test conditions were resumed. After a total time of 249 hours at test conditions, another leak developed in the hot isothermal tubing section upstream of the expansion tank. This leak was patched without removing any of the tubing section, and test conditions were resumed without either changing or sampling the NaK. A third leak occurred at the junction of the expansion tank and the hot isothermal tube after a total time at test conditions of 369 hours and the test was terminated.

Loop NSSA-2A2 operated continuously for 515 hours with no interruptions.

Loop NSSB-1A1 failed in the first heater section after 243 hours at test conditions. The entire first heater was replaced and, although the loop was not decontaminated, it was flushed for approximately two hours at 200 F with NaK. It was then refilled with fresh NaK and test conditions were resumed following the standard procedure. After a total time at test conditions of 353 hours, a failure in the second pump cell with a subsequent failure of the first heater section again necessitated temporary interruption of the test. Both failed sections were completely replaced, the loop was flushed at 200 F, refilled with fresh NaK, and again restarted. In the case of both of the above-mentioned failures, a small specimen of tubing from the hot end of the second heater leg was removed at the time of failure for corrosion analysis, and the results of these analyses are contained in Table VI.

Loop NSSB-3A3 operated continuously at test conditions for 459.5 hours when a leak in the pump cell resulted in termination of the test.

The following metallurgical and chemical analyses were performed by the Materials Laboratory Section of the CANEL Project.

1. Attack and Deposition (NSSA-1A1)

A summary of the corrosion analyses of test loop NSSA-1A1 is contained below in Table III. The original wall thickness of both the heater and cooler sections was 62 mils.

Table III - Metallographic Results of Loop NSSA-1A1

Location	Attack Mils	Deposit Mils	Apparent Wall Decrease, Mils	Remarks
Heater entrance	0.8	0.4	1.5 - 2.0	1. Sparse attack 2. Fine, sparse, metallic deposit
Heater exit (1660)	0.6	--	3.5	Concentrated surface attack
Hot Isothermal Zone, Prior Surge Tank (1660)	1.0	--	3.0 - 3.5	Sparse attack
Cooler (46" total)				
@ 12"	1.5	--	--	Sparse attack
@ 30"	0.4	2.8	--	1. Sparse attack 2. Large, coarse moderately concentrated metallic deposit of 1.5 mils 3. Sparse, fine particles of 1.0 mils at I.D. 4. Platelet deposit of 0.3 mils
@ 42"	0.9	4.2	--	1. Sparse attack * 2. Large coarse concentrated metallic deposit of 4.0 mils 3. Platelet deposit of 0.2 mils

* See Figure 5 for photograph of this deposit

2. Attack and Deposition (NSSA-2A2)

A summary of the corrosion analyses of test loop NSSA-2A2 is contained in Table IV. The original wall thicknesses of the heater and cooler sections are the same as loop NSSA-1A1.

Table IV - Metallographic Results of Loop NSSA-2A2

Location	Attack Mils	Deposit Mils	Apparent Wall Decrease, Mils	Remarks
Heater Entrance	1.0	--	1.5	Sparse attack
Heater exit (1660 F)	1.0	--	1.0 - 1.5	Sparse attack
Hot Isothermal Zone, Prior Surge Tank (1660)	1.0	--	1.0 - 2.5	Sparse attack
Cooler (46" total)				
@ 12"	1.0	--	--	Sparse attack
@ 30"	0.3	--	--	Sparse pitting attack
@ 42"	0.6	0.6	--	1. Sparse attack 2. Fine metallic deposit

3. Attack and Deposition (NSSB-1A1)

A summary of the corrosion analyses of test loop NSSB-1A1 is contained below in Table V. The original wall thicknesses of the heater sections was 30 mils and that of the cooler sections 81 mils. In addition, a summary of the corrosion analyses of the loop sections removed at the time of the intermediate failures is contained in Table VI.

Table V - Metallographic Results of Loop NSSB-1A1

Section	Fluid Temperature, F	Subsurface Void Attack, mils	Sigma Phase - mils	Remarks
1) Entrance 1st Heater	1530	0.8	Across wall - 26	
2) Entrance 2nd Heater	1630	1.0	Across wall - 28	Oxide attack of 6.0 mils at O.D.
3) Exit 2nd Heater	1660	1.0	Across wall - 29	
4) After Surge Tank	1660	4.0	Halfway across wall - 41	
5) Before Cooler	1660	1.0	Two-thirds across wall - 54	
6) Cooler Entrance	1660	0.6	Across wall - 83	
7) Cooler Exit	1530	0.7	Across wall - 81	Zone of 0.9 mils containing gray particles evident at I.D.

COMMENTS

1) No apparent solution attack evident in the specimens.
2) Sigma phase most concentrated at I.D.
3) Subsurface void attack was sparse.
4) All specimens showed a recrystallized structure after test.
5) The cooler I.D. showed a golden-brownish film which XRD indicated to be d-Fe.

Table VI - Intermediate Analyses of Heater Sections of NSSB-1A1

	Specimen* Location	Temp	Type of Attack	Max. Depth Attack	Remarks
A)	1st htr (243 hrs)	1530 F	Subsurface void	0.4 mil	Sparse attack. Sigma phase across wall
B)	1st htr (243 hrs)	1630 F	Intergranular penetration	0.2 mil	Sparse attack. Sigma phase to 20 mils at ID
C)	2nd htr (243 hrs)	1660 F	None Evident	---	Sigma phase to 20 mils at ID
D)	2nd htr (353 hrs)	1660 F	Subsurface void Intergranular penetration	0.3 mil 0.9 mil	Sigma phase occurred intergranularly

* Refer to Figure 2 for location of points A, B, and C

4. Attack and Deposition (NSSB-3A3)

A summary of the corrosion analyses of test loop NSSB-3A3 is contained below in Table VII. The original wall thicknesses of the heater and cooler sections are identical to those of loop NSSB-1A1.

Table VII - Metallographic Results of Loop NSSB-3A3

Section	Fluid Temperature, F	Maximum Depth Attack, mils	Sigma Phase Width, mils	Sigma Phase Free Zone ID, mils	Sigma Phase Free Zone OD, mils
1) Entrance 1st Heater	1530	0.4	27	1-2	---
2) Exit 1st Heater	1630	0.4	23	1-2	3.5-6
3) Entrance 2nd Heater	1630	0.5	18	1-2.5	7.5-8
4) Exit 2nd Heater (Fig 6)	1660	0.8	18	1-3	7.5-9
5) After Surge Tank	1660	0.1	58	1-3	20-22
6) Before Cooler	1660	0.8	48	0.5-3	30-34
7) Middle of Cooler	1600	0.8	82	0.5-1	---
8) Cooler Exit	1530	0.3	82 (across wall)	---	---

COMMENTS

1) No apparent solution attack evident in the specimens.
2) No deposit
3) Attack in all sections except #5 (after surge tank) consisted of concentrated surface pits. Attack in section #5 was subsurface void type.
4) The cooler ID showed a bronze-like film which X-Ray diffraction indicated to be austenite.

5. Attack and Deposition (Summary of all loops)

A summary of the maximum solution attack, maximum penetration-type attack, maximum deposits, and maximum extent of sigma phase at their respective loop locations and the corresponding NaK temperatures in each of the four loops is outlined below in Table VIII.

Table VIII - Summary of Attack and Deposition for All Loops

		Max. Solution Attack	Max. Penetration Attack	Max. Deposit	Max. Sigma Phase
NSSA-1A1	Specimen location	Heater exit	Cooler entrance	Cooler Exit	Not re-ported
	Temp. (°F)	1660	1660	1530	
	Depth (mils)	3.5	1.5	4.2	
NSSA-2A2	Specimen location	Hot isothermal zone	Hot isothermal zone	Cooler Exit	Not re-ported
	Temp. (°F)	1660	1660	1530	
	Depth (mils)	2.5	1.0	0.6	
NSSB-1A1	Specimen location	None	Hot isothermal zone	None*	Cooler entrance
	Temp (°F)		1660		1660-1530
	Depth (mils)		4.0		83#
NSSB-3A3	Specimen location	None	Hot isothermal zone	None*	Cooler exit
	Temp (°F)		1660		1530
	Depth (mils)		0.8		82#

* The cooler ID showed a bronze-like film which X-ray diffraction indicated to be austenite.

\# Completely across tube wall.

6. Chemical Analyses

Chemical analyses were made to determine the oxide content of the NaK prior to the start of each test in addition to a posttest analysis of the NaK at the end of test from loop NSSA-2A2. A summary of these analyses for all four tests is contained below in Table IX. The pretest NaK samples were taken at a fluid temperature of 700 F and the posttest sample at 1530 F. Analyses of all samples were made by the Pepkowitz-Judd amalgamation process.

Table IX - Oxide Analyses of NaK Samples

Loop Title		Oxide Content Pretest	Oxide Content Posttest
NSSA-1A1		750 - 1020 ppm	None Taken
NSSA-2A2		305 - 1575 ppm	1630 ppm
NSSB-1A1	1st fill	113 - 270 ppm	None Taken
	2nd fill	410 ppm	
	3rd fill	300 - 400 ppm	
NSSB-3A3		115 - 290 ppm	None Taken

Subsequent to the running of these four tests, fill procedures have been developed for the in-pile loops which will insure oxide contamination levels between 50 and 60 ppm.

In an effort to determine the nature and composition of the sigma-phase free zone in loop NSSB-3A3, an X-Ray spectrographic analysis of this zone was effected. Further investigation involving a comparative analysis of the heater, cooler, and as-received tubing revealed more chromium in the heater tubing than in the as-received tubing, and the content in each of these was greater than in the cooler tubing. In addition, the iron content of the cooler tubing was greater than that in the as-received tubing, and the content of both of these was greater than that in the heater.

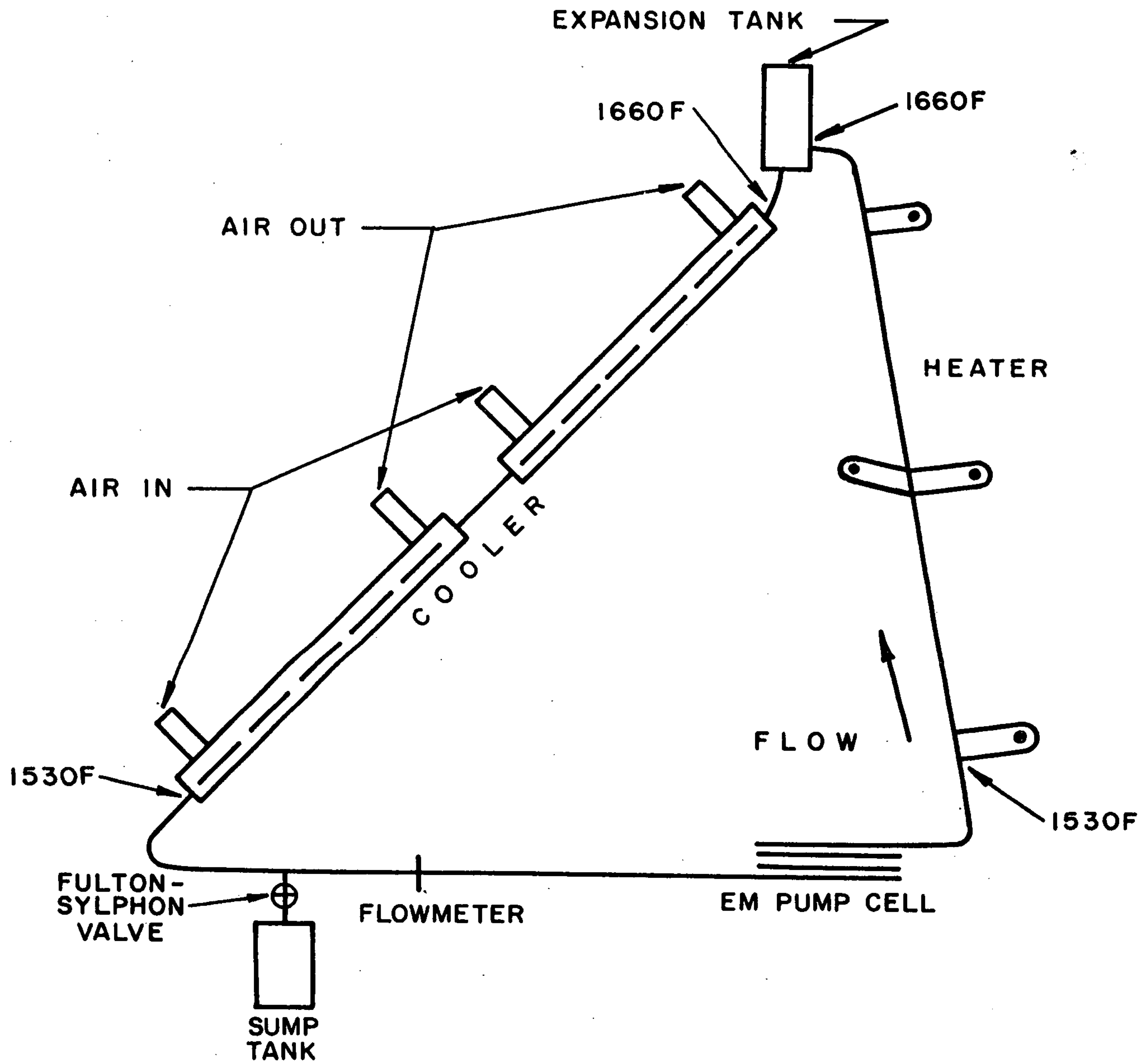
Conclusions

The X-Ray spectrographic analyses of the tubing ID's of loop NSSB-3A3 showed less chromium and more iron in the heater, and more chromium and less iron in the cooler as compared with the as-received material, indicating that the sigma-phase free zone was due to a depletion of chromium in the heater. The absence of a complete chemical analysis, particularly with respect to molybdenum, or a complete annealing and cold-work history of the tubing used in the fabrication of the two types of loops makes it impossible to explain the wide variation in observed sigma-phase between the NSSA and NSSB type loops. Material for all loops was purchased as commercial grade type 316 stainless steel. Although the time-temperature phenomena of the sigma-phase formation is substantiated in test NSSB-1A1 (see Tables V and VI), there is no correlation when comparing the formation of sigma-phase between the NSSA-type loops and the NSSB loops. The formation of the sigma-phase apparently had no effect on the corrosion resistance of the type 316 stainless steel.

Despite the possible introduction of appreciable amounts of contamination through the series of leaks that occurred during two of the tests, type 316 stainless steel appeared in all tests to be a satisfactory container material for NaK under the subject test conditions.

FIG I

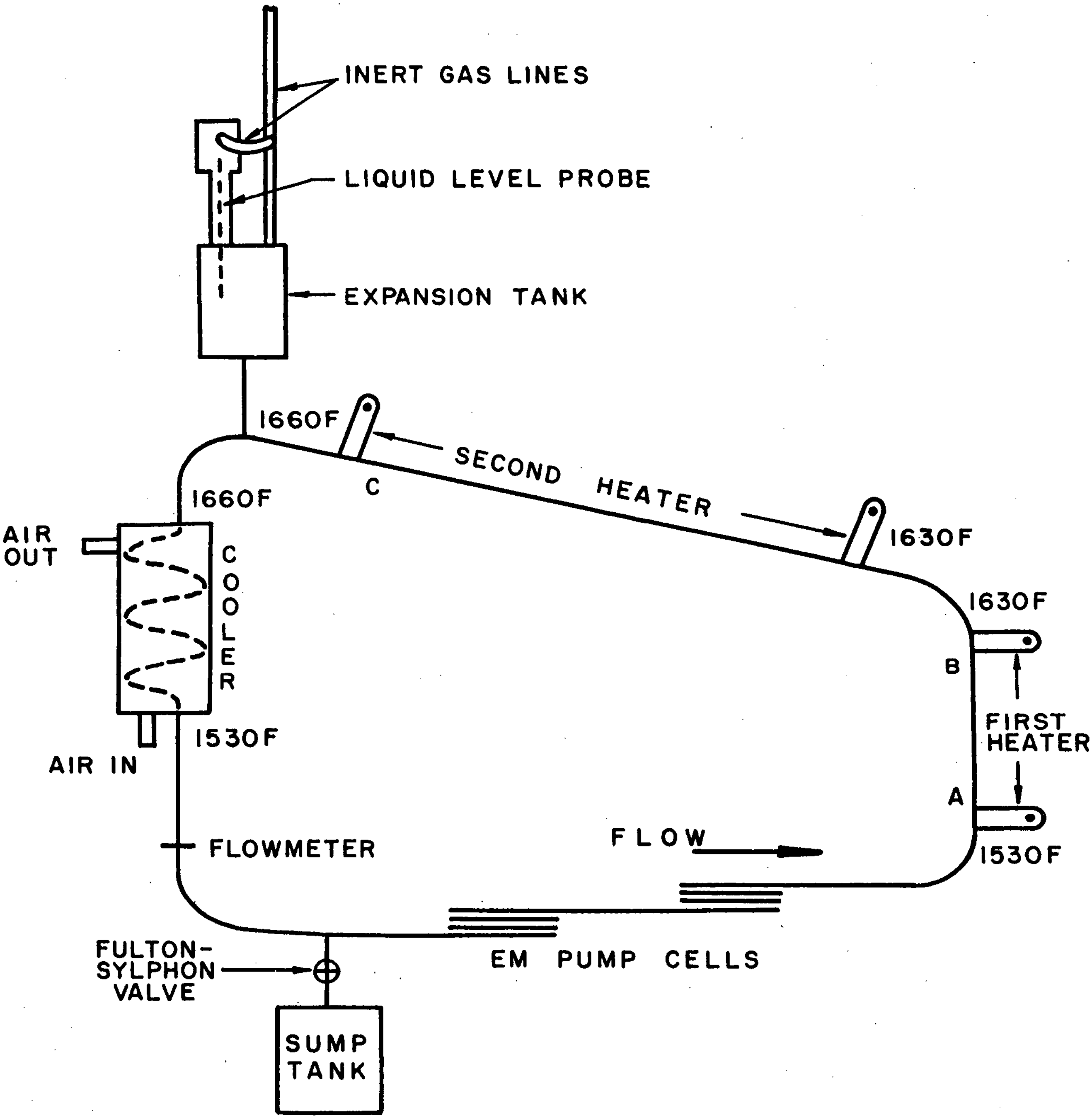
LOOP SCHEMATIC
NSSA-IAI AND NSSA-2A2



[redacted]

FIG 2

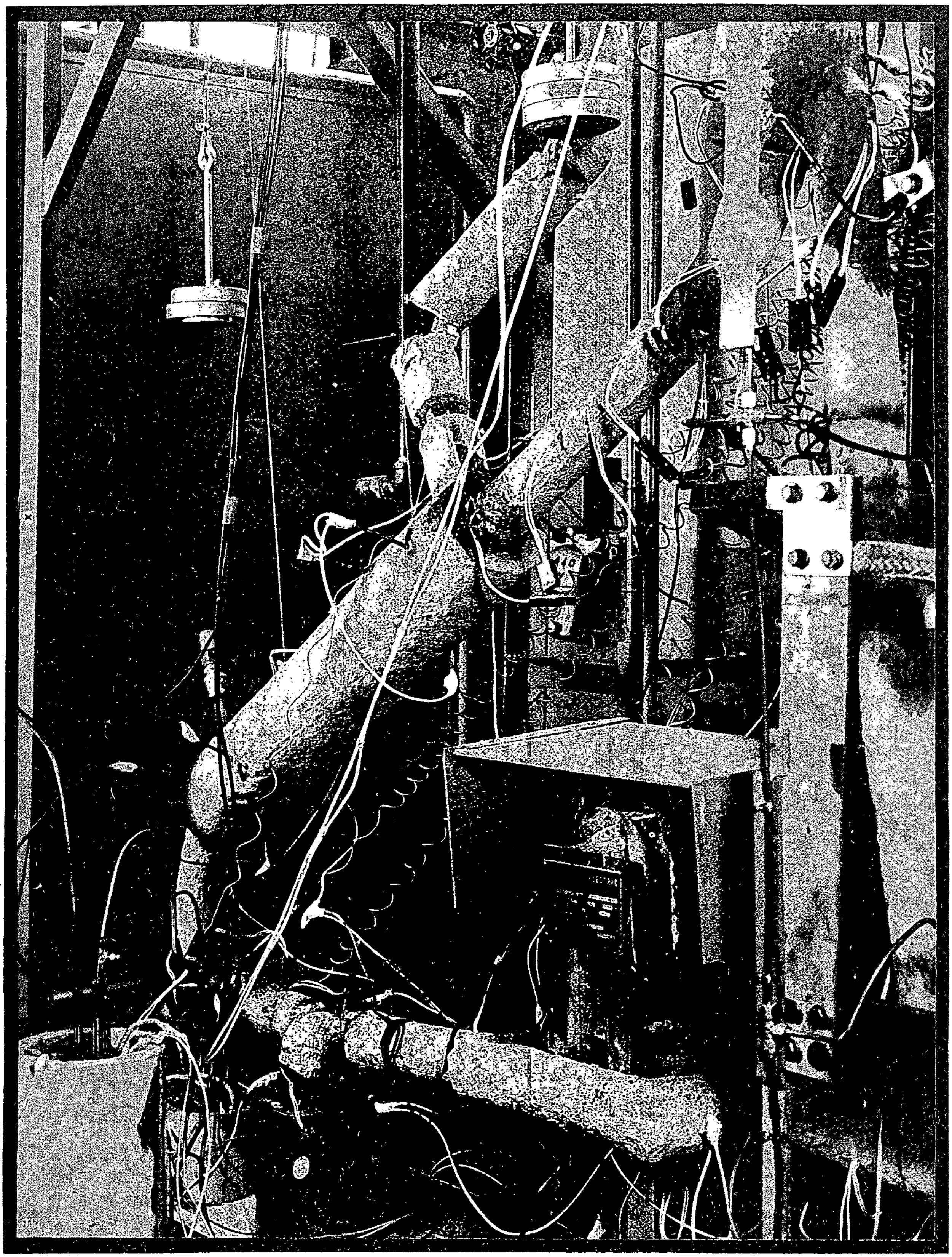
LOOP SCHEMATIC
NSSB-1A1 AND NSSB-3A3



[redacted]

FIG 3

TYPICAL INSTALLED TEST LOOP



[redacted]

FIG 4

TYPICAL TEST STAND CONTROL PANEL

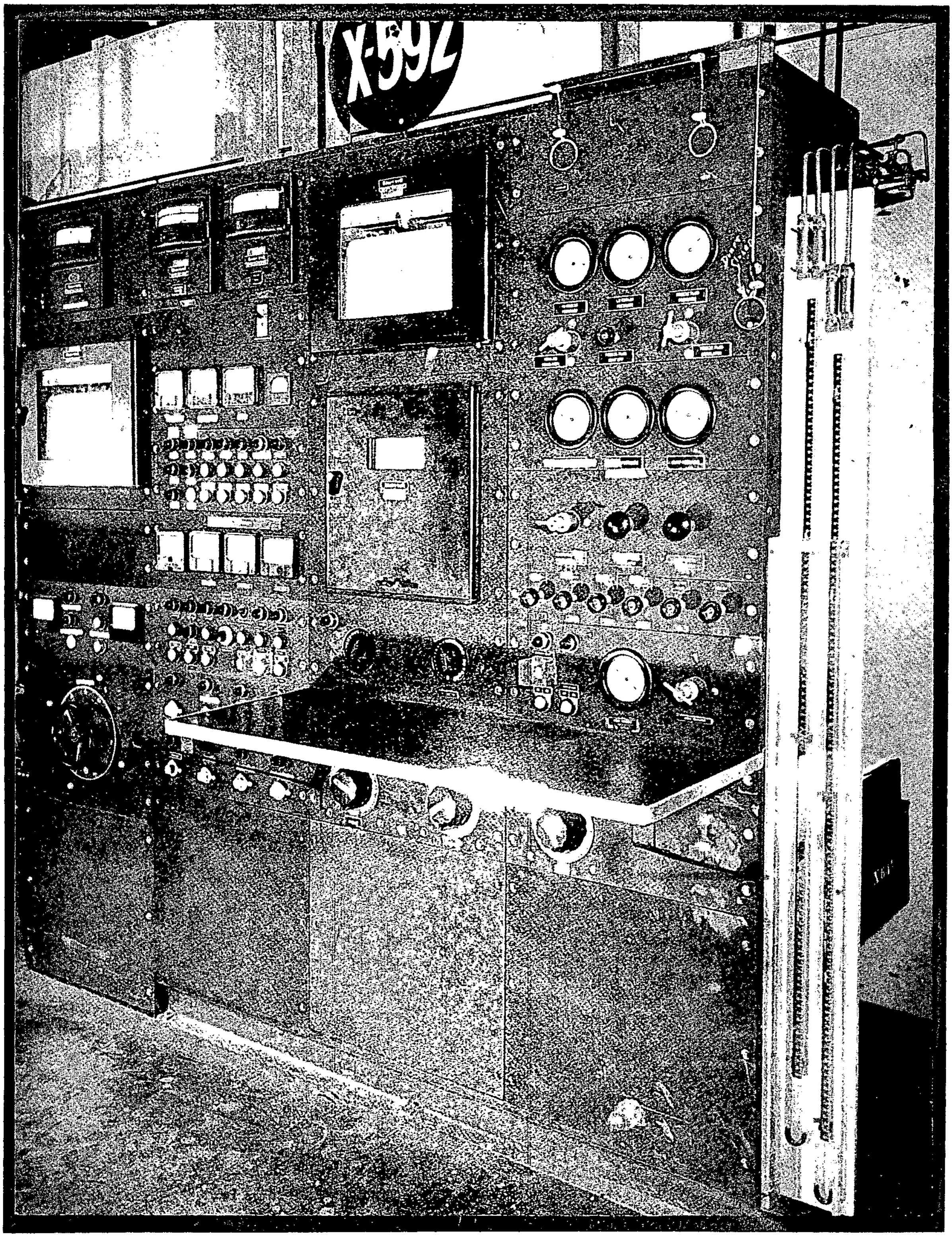
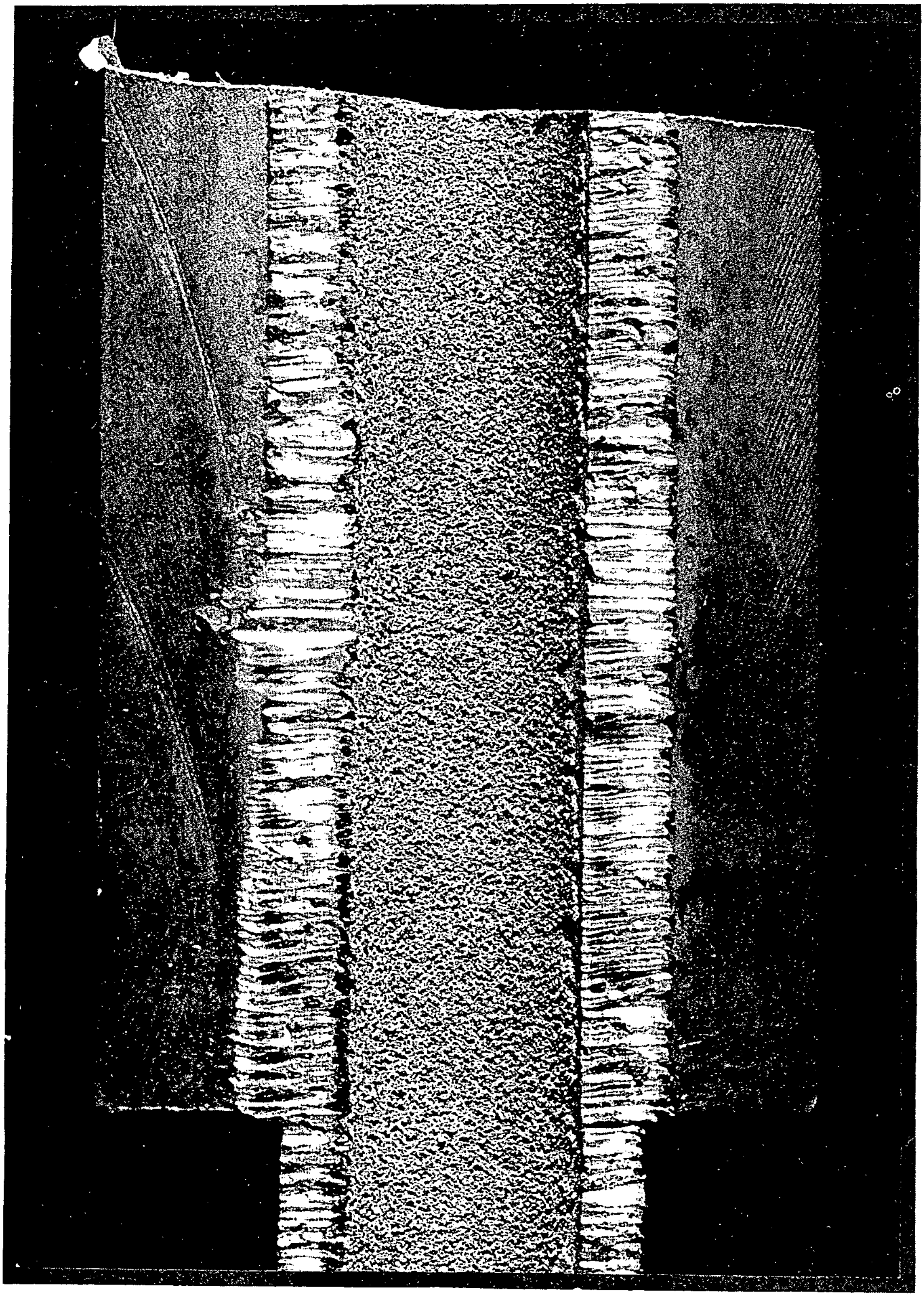


FIG 5

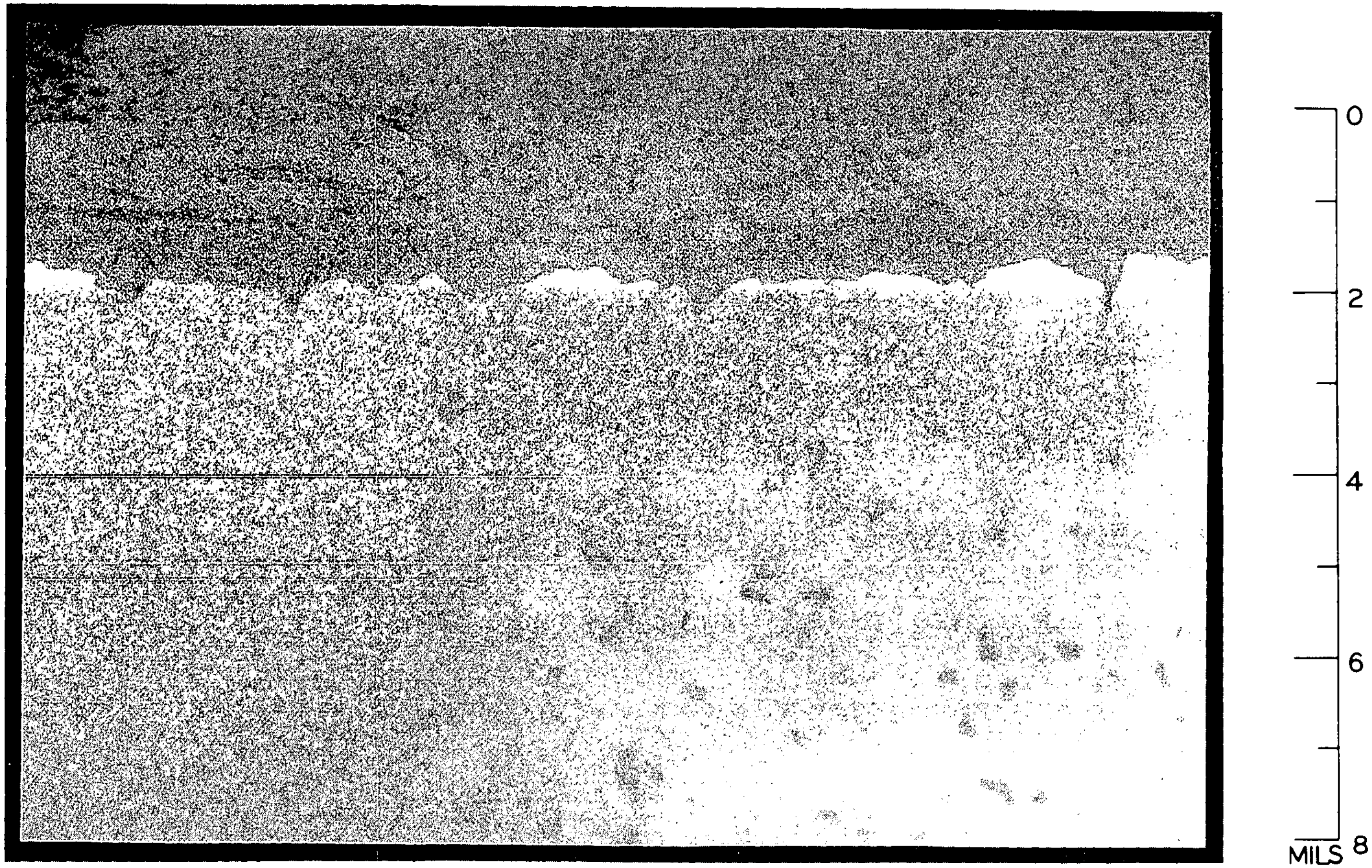
PHOTOGRAPH OF TRANSVERSE COOLER SECTION

LOOP NSSA-1A1



SHOWING MASS TRANSFER AT DOWNSTREAM END OF SECOND COOLER

PHOTOMICROGRAPH OF HEATER EXIT OF LOOP NSSB-3A3



ETCHANT: 10N NAOH, ELECTROLYTICALLY

MAGNIFIED: 500X

SHOWING (1) PITTING ATTACK (2) SIGMA PHASE THROUGHOUT BULK OF WALL THICKNESS (3) AREA AT I.D. LEAN OF SIGMA PHASE.

FIG 6

APPENDIX A

Sample Calculations for Determining Loops Operating Conditions

The following sample calculations are typical of those used to determine the test conditions existing in all four of the loops reported in this memorandum. The three methods of calculating the flow conditions in the loops are: 1) by the flowmeter reading, 2) by main heater heat balance, 3) by cooler heat balance. The data used here was taken directly from the data sheets of test loop NSSB-3A3 after 250 hours of operating time.

I. Velocity Determination Using the Flowmeter

A permanent magnet type flowmeter installed so that the flowing NaK cuts through its magnetic lines of force will generate an EMF perpendicular to the magnetic field and the flow of NaK. Two wires attached to the NaK carrying tube and between the poles of the magnet in the plane of the generated EMF complete a circuit to a strip chart recorder. By knowing the calibration of the strip chart, the type and dimensions of the flowmeter tube and the field density, in gauss, of the magnet, the velocity of the NaK can be calculated using Elrod's equation (1):

$$E = BVd \times 10^{-5} \frac{2\left(\frac{d}{D}\right)}{1 + \left(\frac{d}{D}\right)^2 + \frac{\rho_F}{\rho_W}\left[1 + \left(\frac{d}{D}\right)^2\right]} \qquad (1)$$

Where

- E = reading obtained in Millivolts
- V = velocity in cm/sec
- B = gauss of permanent magnet
- d = I.D. of tube in cm
- D = O.D. of tube in cm
- ρ_F = electrical resistivity of fluid
- ρ_W = electrical resistivity of tube wall

The following data and information was available

Fluid: NaK, ρ_F = 43.3 microhm-in (1)
Tube: Type 316 stainless steel, .859 cm I.D., 1.27 cm. O.D. ρ_W = 47 microhm-in (2)
Permanent Magnet: Flux density, 2030 gauss
Strip chart range: 0 to 100 on chart = 0-10 millivolts
Strip chart reading: 25.5 or 2.55 millivolts

Rearranging equation (1) and solving for the velocity through the flowmeter

$$V = \frac{E}{Bd \times 10^{-5} \dfrac{2\left(\frac{d}{D}\right)}{1 + \left(\frac{d}{D}\right)^2 + \frac{\rho_F}{\rho_W}\left[1 + \left(\frac{d}{D}\right)^2\right]}} \qquad (2)$$

$$V = \frac{2.55}{(2030)(.857)\times 10^{-5}\;\dfrac{2\left(\frac{.857}{1.27}\right)}{1+\left(\frac{.857}{1.27}\right)^2+\frac{43.3}{47.0}\left[1-\left(\frac{.857}{1.27}\right)^2\right]}}$$

V = 331.3 cm/sec or 10.87 ft/sec through the flowmeter.

With a .190 in I.D. heater leg, the heater leg velocity is:

$$V_{HEATER} = V_{FLOWMETER} \times \frac{\pi R^2_{FLOWMETER}}{\pi R^2_{HEATER}} = 10.87\left(\frac{.338}{.190}\right)^2 = 35.9\ \frac{FT}{SEC} \quad (3)$$

II. Velocity Determination Using a Main Heat Balance

The current supplied to the heater leg generates heat in both the tube wall and the NaK. By knowing the output of the transformer, the amount of estimated heat lost through the insulation in the heater leg, the temperature change of the NaK in the heater leg from the entrance to the exit, and the heat capacity and density properties of the NaK, a heat balance can be made to determine the NaK velocity through the heater leg. The following information and data was available:

Transformer Conditions

Amperes - 40.5
Voltage - 395
Kilowatts - 16
Heat loss through insulation - 0.4 KW (1370 BTU/hr)
An experimentally determined power loss of 12% was obtained through the powerstat, transformer and bus bars.

NaK 44 Properties and Conditions

Heat Capacity C_p = 0.25 BTU/lb/°F (1)
Density LM ρ = 44.6 #/ft^3

Δt LM = 130°F

Important Heater Leg Dimensions

ID - .190 in.
Cross Section of NaK = 19.68 x 10^{-5} ft^2

The heat added to the NaK in the heater leg is (13 - 1.2) .88 = 10.38 Kw or converting to BTU/hr is 3415 x 10.38 = 35,450 BTU/hr. (4)

Using the equation q = eVACpΔt where

q = heat supplied to heater leg, BTU/hr
e = NaK density #/ft^3
V = NaK velocity ft/sec
A = cross sectional area of NaK ft^2
Cp = specific heat of NaK, BTU/#°F
Δt = NaK temperature rise through heater, °F

Rearranging the equation to solve for V and substituting gives

$$V = \frac{33,450}{19.68\cdot 10^{-5}\times 44.6\cdot 0.25\cdot 3600\cdot 130} = 34.5\ \frac{FT}{SEC} \quad (5)\ \text{VELOCITY}$$

in the heater leg.

III. Heat Balance Using the Cooling Air

Air was passed over the NaK-containing tubes in the cooler section in an enclosed cooling air system and the flow rate was determined by a flange tap orifice connected to a water manometer. The orifice equation and constant used to determine the volume of air were obtained from the V.D.I. Specifications in NACA bulletin No. 952.

The general flow equation is:

$$W_A = 111.95\, d^2 \alpha \epsilon \sqrt{\frac{P_{abs} \times \Delta P}{T_{abs}}} = lb/hr \qquad (6)$$

Where

D = Pipe diameter
d = orifice diameter
α = orifice coefficient
ϵ = expansion factor
P_{abs} = upstream orifice pressure
ΔP = orifice differential pressure
T_{abs} = absolute air temp. °R

For a 1.00 inch orifice and 1.380 I.D. pipe, the orifice coefficient is:

$(d/D)^2 = .525$

which gives an orifice coefficient of .708.[3]

(7)

The expansion factor used is .993 and the temp. is 88°F or 548°R. Changing the ΔP from psi to inches of water and inserting known factors in equation (6) gives:

$$W_A = 111.95\,(1.00)^2\,(0.706)(0.993)\sqrt{\frac{P_{abs} \times 27.7 \Delta P}{548}}$$

$$W_A = 17.55\sqrt{P_{abs} \times \Delta P} = lb/hr \qquad (8)$$

The heat balance equation used was

$$Q = W_A\, C_p\, \Delta T \qquad (9)$$

Where

Q = BTU/hr removed from cooler
W_A = #/hr of air through cooler
C_p = heat capacity of air through cooler
ΔT = temperature differential of air

Using equation (8) for W_A in equation (9) gives:

$$Q = 17.55\sqrt{P_{abs} \times \Delta P} \times C_p \times \Delta T \qquad (10)$$

The following data was available.

C_p (AIR) = .249 BTU/# F° (3)
ΔT (AIR) = 240 °F
ΔP = 43.4 inches of water
$P_{abs.}$ = 28.5 #/in²

Substituting in equation (10) the BTU/hr removed from the cooler was calculated to be:

$$17.55 \sqrt{(13.8 + 14.7)(43.4)} \times .249 \times 240 = 36,810 \text{ BTU/hr} \qquad (11)$$

From equation (5) this is equal to 35.8 ft/sec velocity in the heater. Due to the possible error obtained in the transformer efficiency, more reliability was placed on the cooling air heat balance and flowmeter velocity when establishing the conditions on the loop.

(1) Liquid Metals Handbook, Sodium-NaK Supplement 3rd Edition 1955, AEC - Dept. of Navy Washington, D.C.

(2) FXM-3419

(3) NACA Bulletin #952 p 68, Figure 20