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QUARTERLY TECHNICAL PROGRESS REPORT
LMFBR SAFETY PROGRAMS
JANUARY-MARCH 1970

AEC Research and Development Report

Atomics International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304

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The preceding Quarterly Technical Progress Report
was AI-AEC-12912.

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Program: Reactor Development

AEC Task: 6-D and E, Nuclear Safety, Gaseous Effluents, Sodium Fires

Project Manager: H. A. Morewitz

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I. PROJECT OBJECTIVES

The general objective of this project is to develop experimental information and analytical methods which characterize the release and transport of effluents and energy generated during major Liquid Metal Fast Breeder Reactor (LMFBR) sodium accidents. The source of energy generation may be from the escaping coolant, by rapid thermal energy transfer, and/or by combustion of the sodium coolant. The effluents may be sodium (as ^{24}Na) or its oxide, fuel materials, and fission products available as potentially serious dispersions of radioactivity. The information to be developed is required for the design and safeguards analysis of economical, sodium-cooled fast reactors. The objectives of this project correspond to those of Task 10-2.6 and -2.7 of the LMFBR Program Plan, Section 10 Safety (WASH 1110). The results and technology obtained from this project are being applied for the safety analysis and engineering safeguards design for the Fast Flux Test Facility (FFTF).

II. MAJOR ACCOMPLISHMENTS DURING FISCAL YEAR 1970

The approximation solution of the heterogeneous aerosol agglomeration model programmed as HAA-3 has been modified to correctly compute the decrease in airborne particulates when the log-normal approximation fails. The constant-input source term and the leak term have been modified so that time variable functions can be studied.

The theory of efficiency of gravitational collisions between aerosol particles has been reviewed and found to be somewhat deficient. However, to study the

effect of gravitational agglomeration efficiency, HAA-3 has been modified to include an efficiency term that can be varied from zero to one independently of particle size.

The approximation solution of the heterogeneous aerosol agglomeration model programmed as HAA-3 has been extended to include the optional use of the Klyachko velocity correction to Stokes Law. This leads to a more accurate solution for high initial airborne concentration cases which have numerous particles with Reynolds numbers greater than 0.5 and ranging up to at least 400. For this range of Reynolds numbers the settling velocities computed from Stokes Law are too fast, leading to an incorrect evaluation of the fate of the aerosol.

Four reports have been written and issued:

- 1) "Characteristics of Aerosols Produced by Sodium Fires, Vol. II, Comparison of Experiment with a General Equation for the Coagulation of Heterogeneous Aerosols," M. A. Greenfield, R. L. Koontz, and D. F. Hausknecht, AI-AEC-12878.
- 2) "The Effect of Aerosol Agglomeration on the Reduction of the Radiological Source Term for the LMFBR Design Basis Accident," R. L. Koontz, R. S. Hubner, and M. A. Greenfield, AI-AEC-12837.
- 3) "An Approximate Solution to the Equation for Aerosol Behavior," R. S. Hubner, AI-AEC-MEMO-12880.
- 4) "Description of Sodium Fires Test Installation," R. P. Johnson, R. N. Cordy, and S. R. Price, AI-AEC-12759.

In addition to previous sodium-pool-fire modeling tests a fourth was carried out in the Large Test Vessel (LTV) in an air atmosphere, a fifth in a 10% atmosphere, and a sixth in a 2% environment, all with 50 lb of sodium.

An improved sodium-pool-fire accident code, designated SOFIRE II has been programmed for computing the thermal behavior of a large sodium fire. The code is set up for configurations such as closed cells (1-cell) and two interconnected volumes (2-cell) such as a primary vault open to the reactor building in an LMFBR.

A preliminary spray-fire model has been developed which aids in interpreting the experimental adequacy of the measured parameters such as oxygen concentration and wall temperature as a function of time in the Spray-Test Vessel (STV). Improved instrumentation and equipment for conducting multiple spray test in the STV have been installed and checked out.

III. PROGRESS DURING REPORT PERIOD

A. SPRAY-FIRE EXPERIMENT

During this report period considerable effort has gone into the construction of new instrumentation for the STV. The need for more rapid data acquisition had been demonstrated by the unpredictability of spray fires. It was noted that without improvements to the STV one would not be able to collect enough data to cover the subject in a reasonable time. Therefore, several modifications to the previous apparatus were constructed. These improvements include a modified spraying system for more precisely controlled sprays and less downtime, an FM tape recorder with dc data-conditioning amplifiers and plotting equipment, a programmer to control the electromechanical functions of each test, and a pneumatic scale with a high enough damping coefficient to be relatively undisturbed by shocks.

The STV had previously been equipped with an internal sodium melt and spray pot which had to be loaded before vessel closure for each experiment. The vessel downtime was a minimum of five days per test while extensive aerosol studies were being made simultaneously (i. e. plating, fallout, spray distribution). In addition the vessel was opened after each test and extra time was lost reloading the sodium for the next test.

The base of the STV was modified as per Figure 1. The modifications consist of four separate spray lines and nozzles, each resistance-heated with connections for an external spray-pot. The base was also modified to accept a pneumatic fallout scale which could be nulled at will. The combination of these changes provides that four spray-fires may be made before the vessel is opened.

The pneumatic scale (Figure 2) was designed to provide continuous fallout data with minimal second-order response to falling droplets or convection

Figure 1. Spray-Test Vessel, Base-Plate Modification

Figure 2. Pneumatic Scale

currents. Full-scale loads can be applied instantaneously and read within 1/2 sec. Differing from the previous turntable method of fallout collection, the data are immediately available and require no chemical analysis. Data from a previous fire can be nulled for the next experiment.

In conjunction with the multiple-spray adaptation of the STV base-plate, a rack-mounted spraying system was constructed. It has sodium-storage capacity for up to ten spray fires and the storage section prefilters the sodium as it enters the spray pot. The depth of the sodium is measured using a conductivity probe which provides for 1/4-gm accuracy. The probe, an ungrounded junction thermocouple (TC), is also used for thermostatic control of the sodium temperature. As the sodium is released by a pneumatic valve and sprayed, the argon drive pressure is controlled and measured by a differential pressure regulator and transducer referenced to the vessel atmosphere.

The FM tape system purchased and installed this quarter will record thermal, pneumatic, and atmospheric data from dc signals conditioned by low-noise signal amplifiers. The dynamic record thus obtained will be plotted directly by an X-Y recorder. Once the magnitude of the time base has been chosen the trigger module can shift the time ordinate at will to accommodate interesting data periods throughout the test. After analog plotting, the data will then be digitized for tabulation and computer-model comparisons. A programming module using punched tape, slave relays, and an accurate time control was constructed which controls all the actuation function as well as the start and termination of the spray fire. The module can be patchboarded easily to accommodate a variety of complex and rapid operations.

A summary of data to be collected is listed below:

- 1) Drive pressure vs time.
- 2) Vessel pressure vs time.
- 3) Spray-zone air temperature at 3 and 8 ft vs time.
- 4) Vessel internal skin temperature vs time at 2, 4, 7, and 9 ft.
- 5) Vessel external skin temperature vs time at 4 and 7 ft
- 6) O₂ concentration vs time.

- 7) Fallout vs time.
- 8) Aerosol concentration vs time.
- 9) Spray rate (average).
- 10) Chemistry analysis of average aerosol.
- 11) Filtration efficiency of ceramic materials.
- 12) Aerosol size vs time.

B. PHASE II, LARGE TEST VESSEL STUDIES

The sixth large sodium fire experiment in the current single-cell test series was held in the LTV. This test involved 50 lb of 1100°F sodium introduced into the test vessel which contained a 2 vol % oxygen atmosphere at ambient temperature conditions. The pretest system pressure was adjusted to 3.6 psig to accommodate aerosol sampling. The burn pan used in this test was constructed of 100-mil-thick steel to reduce the initial sodium heat losses during the spill period. Comparison of test results for this 2% fire and the previous 10% fire (Test 5) have been made and discussions are given below. A summary of the initial test conditions are shown in Table 1, LTV Pool-Fire Summary.

1. Aerosol Studies

The maximum aerosol concentration for Test 5 (9.5% oxygen atmosphere) was approximately 50 $\mu\text{gm/cc}$ as compared to a maximum concentration of approximately 0.65 $\mu\text{gm/cc}$ for Test 6. The decrease in aerosol concentrations as a function of time for Tests 5 and 6 are shown in Figure 3. In Test 6 sodium metal was airborne while oxide was airborne in Test 5.

The maximum aerodynamic diameter (50% size) measured for Test 5 was approximately 6 μ decreasing to 3.3 μ after 300 min. For Test 6 the particle size decreased from a maximum of 4.1 μ to 3.8 μ for the same time period.

The aerosol-concentration curves for the two tests seems to confirm the particle-size history found from the impactor data. The concentrations converge until approximately 250 min have passed, at which time the concentrations diverge. Since Test 6 produced very little heat from oxidation it may be that the gas environment of the chamber is not being stirred after a long time. Tranquil settling would cause the airborne mass to decrease at a faster rate.

TABLE 1
POOL-FIRE EXPERIMENTS DATA SUMMARY,
LARGE TEST VESSEL (6 ft²)

Parameters	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Introduced Sodium Temperature, °F	955	950	1000	1000	1100	1100
Weight of Sodium Introduced, lb	25	25	44	50	50	50*
Sodium Temperature After Spill, °F	955	950	560	560	650	800
Maximum Bulk Sodium Temperature, °F	1355	1400	1360	1300 - 1400	890	800
Time for Maximum Bulk Sodium Temperature to Occur, min	~18	~18	50	45	28	
Release Fraction of Oxidized Sodium	0.21	0.22	0.40	~0.35	~0.27	†
Oxygen Consumed, %	6.1	6.3	10.6	10.7	5.3	0.34
Vessel Atmosphere (initial), % O ₂	21	21	21	21	9.25	2.0
Average Gas-Temperature Rise, °F	42	36	67	87	49	13
Fraction Sodium Peroxide §			0.69	0.39	0.78	†
Peak Pressure Rise (ΔP), lb/in. ²	1.34	1.16	2.14	2.77	1.59	0.41
Measured Peak Concentration of Sodium in Vessel Atmosphere (one location), $\mu\text{gm/cc}$			~60	~100	70	0.65
Time for Peak Concentration, min		15	45	50	25	15
Fallout Halftime After End of Burning, min	10	6	12	13	15	
Aerosol Concentration Halftime After End of Burning, min		9.5	10	8	~18	100
Error in Mass Balance, lb			<1	-4.7	<1	
Deposition Ratio, Plating/Fallout			0.11	0.10	0.045	†
Pounds of Oxygen Consumed per ft ² per hr			4.4	5.2	1.8	
Humidity, Initial, ppm	8,000	10,000	6,400	6,500**	3,300	1,750

*Preliminary

†Analysis in progress

§Fraction of oxidized Na found on floor which is peroxide

**Insulation contained moisture

Figure 3. Aerosol Concentration (average)

During Test 6 an attempt was made to collect an aerosol sample on an impactor stage suitable for examination on an optical microscope. Since each stage of the impactor is calibrated in terms of an aerodynamic property $\sqrt{\rho}d$ (where ρ = density in gm/cm^3 and d = diameter in microns) an attempt was made to measure the diameter and compute the density. A photograph of a typical stage is shown in Figure 4. Observation of the photograph indicates that some flattening of the particles may have occurred during the impaction, since a large portion of the particles are in focus with a common height of $\sim 6\mu$. The large particles were reduced in height to $1/4 d$, and the average computed spherical diameter is approximately 14μ . (See Particle A, Figure 4). The stage constant for this slide has a value of $d\sqrt{\rho} = 5.5$. Thus the computed density is approximately 0.15 gm/cm^3 . Using the next size shown in Figure 4 (labeled B) a reduction in height of $1/2$ occurs and the computed density is approximately 0.19. The particle with a diameter of 6.5 micron (C) has no reduction in height, and hence the computed density is 0.71 gm/cm^3 . The smaller individual particles (D) which have a diameter of approximately 3.5μ are probably produced

Figure 4. Impactor Stage Showing Particles

from larger ones which may have fractured during impaction, and thus no estimates of the density should be made. It can be seen that the aerosol effective density on this stage is much less than the ideal density of sodium metal ($\rho = 1.0 \text{ gm/cm}^3$). Other stages show similar results.

2. Energy

It can be noted in Table 1 that the spill temperatures of Tests 5 and 6 were the same but the resulting equilibrium sodium temperatures after the spill were 640 and 900°F for the two tests respectively. This was accomplished by decreasing the heat capacity of the burn pan.

The experimental data collected during Test 6 indicated that the final resulting system pressure and temperature increase were due primarily to heat transfer from the sodium pool by convection and radiation. The observed system pressure is best predicted without taking oxidation into account (see Figure 5). This also is apparent on the sodium-pool temperature-history curve, Figure 6.

3. Chemistry

Because the heat of formation of sodium oxides is the major cause of the pressure rise associated with sodium fires and because there is nearly a factor of two difference in this heat per mole of oxygen when peroxide is formed instead of monoxide, a rigorous chemical analysis of the Phase-II pool-fire oxidation products is desirable. The results of the first such analysis (Test 5) are discussed below.

The aerosol released by this 10% oxygen atmosphere fire was primarily sodium peroxide (77%) while the instantaneous percent peroxide was a strong inverse function of fire temperature. Only 29% of the total oxide was released by the fire, and the oxide which was retained in the pan was primarily sodium monoxide (93%). Therefore, the overall heat of formation released was indicative of a 71% sodium monoxide fire.

The free-energy-of-formation calculations for the oxides of sodium show that in a neutral or oxidizing environment the preferred sodium oxidation product is the peroxide up to 1650°F (1190°K). For temperatures as low as 1100°F

Figure 5. Phase-II Test 6 System Pressure Rise
(Initial pressure = 3.6 psig)

Figure 6. Phase-II Test 6 Average Sodium-Pool Temperature

the equilibrium constant for the conversion of sodium peroxide to sodium monoxide by decomposition is large enough to produce detectable amounts of the monoxide. Binary statistics indicate that sodium peroxide is an intermediate in the formation of sodium monoxide. Noting that the sodium surface temperatures are in this range or higher, one would predict that the percent of monoxide formed should be a strong function of the flame temperature or rate of reaction. It was found that aerosol samples taken over the fire (see Figure 7) during the hottest period of the test were the highest in monoxide (61%) while those taken both earlier and later during the fire were lowest (18% and <40%).

One would also expect an oxide sample collected very near but not in the fire to be much higher in peroxide than the average fallout sample because the former would have been maintained at a lower reactive temperature for a long period of time. Such a fallout sample (sample E of fallout) did show a 90% peroxide composition compared to the 76% average. In the burning-sodium pool itself any sodium peroxide formed would be subjected to the strong reducing action of sodium vapor. The monoxide would then be the favored oxide. As expected the average peroxide content of the burn pan was 4.3%, with a maximum of 22% for a small layer on the surface. It is possible that the peroxide in the pan may all have been formed while the sodium pool was cooling after the "fire."

In many respects the most interesting observations were those of the physical nature of the burn-pan contents. The sodium had quite obviously used its oxide as a wick to climb to the burning zone, rising as much as 4 in. above the original pool level. The specific gravity of the sodium-pan contents had gone down to 0.25 gm/cc (14.7 lb/ft³) making it a very porous spongy mass.

Chemical-analysis (Table 2) and mass-balance (Table 3) listings have been provided for greater clarification of the trends discussed.

Table 4 shows conclusions that can be drawn from the chemical analysis so far. This tabular presentation is the same as thermodynamics would predict and future modeling should take the data into account. As yet no theory has been developed to accurately predict the temperature of the oxidizing sodium (reaction zone) so that the rates of monoxide and peroxide formation have been undefined as well as the equilibrium proportions of these species.

Figure 7. Location of Chemistry Samples, Phase-II Test 5

TABLE 2
CHEMICAL ANALYSIS PHASE II, TEST 5

Sample Location*	Peroxide (%)	Monoxide (%)	Free Sodium (%)	Percent of Total Monoxide Produced	Percent of Total Peroxide Produced	Description
Crust: A	22.5	77.5	-	7.8	9.40	White layer
B	17.5	82.5	-	4.5	4.02	Thin yellow powder layer
C	12.3	85.6	2.1	6.5	4.20	Black stalks
D	-	53.0	47.0	34.0	0	Silver lump
Weighted Average	6.3	63.2	30.5			
Sodium Pool: A	-	54.5	45.5	18.8		
B	-	53.0	47.0		0	Crumbly silver layer
C	-	53.4	46.6			
Average	-	53.6	46.4			
Fallout: A	78.0	22.0	-			Divided sample of white fallout
B	77.1	22.9	-			(B) deposited first
C	76.0	24.0	-	28.4	82.4	White powder
D	76.3	23.7	-			White powder
E	83.3	16.7	-			Divided sample of white fallout
F	90.5	9.5	-			(F) deposited first
Aerosol: A	-	-	-	-	-	Sample lost
B	82.0	18.0	-	-	-	Sampled at 10 min
C	73.6	26.4	-	-	-	Sampled at 20 min
D	39.0	61.0	-	-	-	Sampled at 30 min
E	59.0	41.0	-	-	-	Sampled at 40 min
Oxide: Released	77.0	23.0	-	28.6	82.4	
Remain- ing in Pool	7.0	93.0	-	71.5	17.6	
Total	28.7	71.3	-	100	100	

*See Figure 7.

TABLE 3
MASS BALANCE PHASE II, TEST 5

Parameters	Weight (lb)				Released Ratio
	Sodium Below Crust	in Crust	Fallout	Total	
Na and Na ₂ O _x	16.5	35.9	13.6	66.6	0.206
Free Na (Na ⁰)	7.6	10.9		18.58	0
Total (Na)	14.2	28.9	8.5	51.6	0.166
Na ₂ O	8.9	22.7	3.0	34.6	0.086
Na ₂ O ₂		2.26	10.6	12.86	0.824
Na ₂ O _x	8.9	24.96	13.6	47.46	0.287
Consumed Na	6.6	18.6	8.5	33.1	0.266

TABLE 4
CHEMICAL-ANALYSIS CONCLUSIONS

Fire Type	Formed	Airborne	Fire Description	
			Temperature (°F)	Oxide Environment
Spray (2% O ₂)	Peroxide	Peroxide	< 1600	Oxidizing
Spray (21% O ₂)	Monoxide	Monoxide	> 1600	Oxidizing
Pool (2% O ₂)	Monoxide	Peroxide	< 1600	Reducing
Pool (21% O ₂)	Monoxide	Monoxide*	> 1600	Reducing

*Airborne oxide will convert slowly to peroxide if possible.

C. ANALYTICAL DEVELOPMENT

1. Aerosol Modeling Gravitational Collision Efficiency Studies

The problem of the "efficiency" of gravitational collisions between aerosol particles has been reviewed. This problem arises because the air, moving around a particle on streamlines that never reach it, tends to carry other particles on such paths, thus preventing collisions. Theoretical work reported on this problem, e.g. in N. A. Fuchs "The Mechanics of Aerosols," (Pergamon, 1964), is still sparse. Thus the effect of the finite extension of the particles in producing collisions even where their centers move on streamlines is never treated simultaneously with the effect of the inertia of the particles in producing collisions by keeping the paths of the particles closer to straight lines than the streamlines are. Even the separate treatments of these two effects are not reliable, since the particles are assumed to be spherical when in fact they are not (which not only affects the geometry of the collisions, but greatly modifies the streamlines), the distortion of particle trajectories by their Brownian motion is ignored, and the interactions of the two colliding particles with the air are handled quite unsymmetrically. Experimental data are particularly sparse, providing hints and suggestions rather than facts and conclusions; the tendency is for the experiments to indicate efficiencies higher than calculated by the theory. This also appears to be the direction of the corrections for the above-mentioned omissions from the theory.

If the best available theory of collision efficiency, defective as it is, were used in calculations of aerosol behavior, it is believed that the effectiveness of gravitational agglomeration in promoting settling of the suspended particles would be substantially reduced. The success of current calculations (where efficiency is taken as unity) in reproducing the results of small- and large-scale experiments is then another reason for believing that the current theory underestimates efficiency. Until the theory of efficiency is much improved there is little reason to believe that its inclusion in the calculations will make them more realistic.

However, in order to get some feeling for the effect of the efficiency being less than one, the HAA-3 code was modified so that a constant efficiency, ϵ , equal to or less than one could be used for the gravitational collision rate.

Figure 8. Effect of Collision Efficiency, True Density

The version of HAA-3 with selectable collision efficiency was used to compare the computed behavior with experiments performed in the LTV. The settling velocities and gravitational agglomeration rates in these calculations were computed using the ideal density and a reduced density of one-quarter the true density. Figures 8 and 9 show calculated air concentrations and fallout data compared to the Phase-II Test-5 experiment. It is clear that the best fit to the experiment is obtained with reduced densities and collision efficiencies near unity. It can be seen that low collision efficiencies give computed results which differ greatly from experiment.

2. Sodium-Pool Fire Modeling

The prediction of the pressure rise and aerosol release as a result of a sodium spill largely depends on the understanding of the burning mechanism. The physical model which was developed to describe the sodium/oxygen reaction is based on the assumption that the burning rate is controlled by the rate of oxygen arrival to the surface of the liquid sodium. Experiments are run to check the validity of this assumption. The major difficulty in comparing the experimental data with the theoretical predictions is the uncertainty in the determination of the composition of the reaction products. A comparison between the theoretical and the experimental oxygen-consumption rate is shown in Figure 10 for Tests 3, 4, and 5. The two theoretical curves drawn for the air and the 9.2% O₂ tests represent the uncertainty in the determination of the mass-transfer coefficient.

This uncertainty stems from the fact that the test geometry is more complex than those for which equations for calculating the mass-transfer coefficient are available.

In the light of the above discussion the agreement between theory and experiments is considered satisfactory.

The general conclusions from the analysis of Tests 3 and 4 are listed below:

- 1) The reaction products during the sodium/air reaction consists of both sodium oxide (Na₂O) and sodium peroxide (Na₂O₂). From heat-balance considerations it appears that the composition of the mixture of the products varied during the experiment.

Figure 9. Effect of Collision Efficiency, Reduced Density

Figure 10. Comparison Between Theoretical and Experimental Oxygen-Consumption Rates

- 2) The apparent fraction of Na_2O in Test 4 was approximately 2.5 higher than in Test 3 which was supposed to be a duplicate of Test 4.
- 3) With the exception of the initial 2 min of the experiment the effective emissivity of the gas can be considered to be unity.
- 4) The fraction of the energy which radiated from the sodium surface and was absorbed by the gas was found to be unity during the first 20 min and then decreased with time. Since this fraction (the interchange factor) depends only on the effective surface emissivity, the emissivity is not a constant.
- 5) The effective thermal conductivity of the oxide layer was found to decrease with time. This could be expected because the fraction of liquid sodium decreases with time while the fraction of vapor in the oxide increases.

3. Sodium Model Parametric Survey

A study has been made to investigate the effects of various parameters on the pressure and temperature rise in reactor containment resulting from a

sodium-pool fire in an air environment. The geometry chosen for this study consisted of two cells, e.g. a primary-system equipment vault which is open via the equipment access hole to the outer containment.

The parameters which were varied in this study were:

- 1) Volume ratio of the two cells.
- 2) Height and width of the vertical opening.
- 3) Insulation thickness of the walls.
- 4) Mass of sodium.
- 5) Radiation exchange coefficient between the sodium surface and the gas.
- 6) Composition of the reaction products.

Results indicate that of all these variables the area of the opening and the composition of the reaction products have the most significant effect on the maximum pressure rise in the outer containment. For example, if the reaction products consisted only of Na_2O the maximum pressure rise in the cell would have been 40% higher than if the reaction products were Na_2O_2 . If the cell opening is increased from 10 to 20 ft in diameter the pressure is increased 80%.

IV. EVALUATION OF EFFORT

Review of the theory of efficiency of gravitational collisions between aerosol particles, and comparisons of HAA-3 with experiments in the LTV both indicate that use of reduced efficiencies considerably lower than unity is not justified for aerosol calculations. In the comparisons of HAA-3 with sodium-oxide aerosol data in the LTV, variation of collision efficiency and particle density clearly showed the experiments are best fitted with reduced densities and collision efficiencies near unity.

Experimental measurements on the in-situ aerodynamic-particle density during LTV tests required to confirm the magnitude of density reduction are currently being planned.

The LTV has been used to study the thermal characteristics and aerosol behavior for a 6-ft² 1100°F Na spill into a 2%-O₂ environment. The reduced burning rate, pressure, and consumed sodium show the mitigating effects of a 2%-oxygen environment.

Because of the differences between the oxide formation of Tests 3 and 4 some additional experiments, duplicating the same initial condition should be made. In doing these experiments it will be necessary to prevent the introduction of water vapor into the system (e. g. from burn-pan insulation, etc).

There is still little difference in the observed reduction rate of the air concentration in the LTV after about 2 hr have elapsed from the beginning of the fires even with an initial concentration of 0.65 $\mu\text{gm}/\text{cm}^3$. The air concentrations and particle-size distribution during burning and up to 2 hr were ascertained and some improvement in sampling showed a reduced density indeed existed. The oxidization products which are produced in a sodium-pool or spray fire have been found experimentally to be near to those predicted by thermodynamics. Future Phase-II and spray-fire tests should continue to verify these results.

V. NEXT REPORT PERIOD ACTIVITIES

Experimental and analytical investigation of sodium sprays, pool fires, and UO₂ vaporization will be made. Several aerosol experiments will be investigated in the LTV, such as UO₂ vaporization and low-concentration sodium-oxide studies.

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Program:	Fast-Reactor Development		
AEC Task:	6-G, Nuclear Safety (Kinetics), Boiling Studies for Sodium Reactor Safety		
Project Manager:	H. A. Morewitz		
Reporting Period:	January-March 1970		
General Order:	7702	Subaccount:	13410
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I. PROJECT OBJECTIVES

The general objective of this project is to develop basic information on two-phase flow and boiling required in the safety evaluation of LMFBR designs. This information is important because of the key role that sodium boiling plays in reactor dynamics, in fuel-meltdown accidents, and in the ultimate shutdown mechanism of the reactor. Specific objectives of the experimental program include the development of reliable high-flux heaters; and the measurements of boiling-heat-transfer characteristics, two-phase pressure drop, void fraction, liquid superheating, transient voiding rates and pressures in single channels, and hydrodynamic instabilities. Specific objectives of the theoretical study, in addition to any analyses required to support the experimental work, are: the development of digital computer codes which will predict transient void fraction, flowrate, and heat transfer for single and multichannel sodium flow; and the incorporation of these codes into a general reactor kinetics code.

II. MAJOR ACCOMPLISHMENTS DURING FISCAL YEAR 1970

A total of 415 three-pin three-channel sodium liquid superheat runs were completed for test conditions of 5 psia at: (1) inlet subcooling temperatures of 100, 200, 300, and 400°F at a sodium velocity of 3 ft/sec; and (2) inlet subcooling temperature of 100°F at sodium velocities of 6 ft/sec and 9 ft/sec. Flow-coastdown test conditions were at 5 psia with: (1) inlet subcooling temperature of 300°F at heat fluxes of 200,000 Btu/hr-ft² and 270,000 Btu/hr-ft²; and (2) inlet subcooling temperature of 400°F at a heat flux of 175,000 Btu/hr-ft².

A total of 374 single-channel sodium liquid superheat test runs were completed for test conditions of 5 psia and for fluid velocities of 3 to 9 ft/sec.

Included were 50 flow-coastdown runs in which boiling was begun by a reduction in flowrate at otherwise fixed conditions.

A topical report on the single-channel experimentation, "Studies of Boiling Initiation for Sodium Flowing in a Heated Channel," AI-AEC-12767, was published September 30, 1969.

A topical report on the multichannel sodium boiling code, SODIFAZE, was published February 15, 1970: "SODIFAZE a Steady-State Multichannel Boiling Sodium Code," AI-AEC-12804.

A topical report on the statistical distribution of incipient boiling entitled, "Analysis of the Statistical Distribution of Incipient Boiling," AI-AEC-12906, was published December 31, 1969.

III. PROGRESS DURING REPORT PERIOD

A. SODIUM-LIQUID SUPERHEATING, 3-CHANNEL TEST SECTION

Two hundred and twelve three-pin, three-channel liquid superheat tests were made during this report period. Fifty were run at 5 psia with an inlet subcooling temperature of 400°F at a sodium velocity of 3 ft/sec, and 37 more at 5 psia with an inlet subcooling temperature of 100°F at a sodium velocity of 9 ft/sec. An additional 125 tests were made of the flow-coastdown type where pressure, inlet temperature, heat flux, and initial velocity are established and then flow is reduced until boiling occurs. Fifty of these tests were run at 5 psia with an inlet subcooling temperature of 300°F at a heat flux of 200,000 Btu/hr-ft²; fifty more at 5 psia with an inlet subcooling temperature of 300°F at a heat flux of 270,000 Btu/hr-ft²; and the last 25 at 5 psia with an inlet subcooling of approximately 400°F at a heat flux of 175,000 Btu/hr-ft². The data are now being reduced and will be reported next quarter.

B. ANALYSIS OF SODIUM-LIQUID SUPERHEATING, 3-CHANNEL TEST SECTION

After determining the all-liquid pressure-drop flow characteristics of the three-channel test section (see Figure 5 of previous quarterly progress report, AI-AEC-12914), 415 sodium-boiling-initiation tests were made. From these

runs 203 were reduced (see Table 1) and plotted in terms of bulk superheat vs heat flux. Of the 203 tests, 53 were run at 5 psia with an inlet subcooling temperature of 100°F at a sodium velocity of 3 ft/sec; the second fifty were run under the same test conditions except with a 200°F inlet subcooling temperature; the third fifty under the same conditions except with a 300°F inlet subcooling temperature; and the last 50 were at 5 psia with an inlet subcooling temperature of 100°F at a sodium velocity of 6 ft/sec.

Figure 1 shows a plan view of the locations of the thermocouples which measure sodium temperature at the end of the heated section.

The design of the three-pin three-channel test section was based on the attainment of equal enthalpy rise of the fluid in all channels when the heat inputs to the pins are equal. This was done by making the ratio of heated perimeter to flowrate (for a given pressure drop) identical for all three types of channels. However, the small clearances between the rods and the attendant dependence of the flow channels on mechanical tolerances made achievement of the desired uniformity difficult. This is illustrated below by three runs in which the heat inputs to the pins were virtually equal.

Location Run	Total Temperature Rise of Fluid (°F)				
	1	2	3	4	5
3A-A1	101	117	107	149	135
3A-A2	104	123	109	147	140
3A-B1	203	215	203	212	240

It is seen that although the maximum difference between channels remains about constant, the desired uniformity is more closely approached as the total temperature rise increases, i.e. as inlet subcooling increases.

Figure 2 is a plot of the Group 3A (A1 to A53) data (3.05 ft/sec, 93°F inlet subcooling) in terms of bulk superheat vs heat flux. The superheat existing in each of the five locations at boiling inception is given, and as the heat fluxes among the channels differ, it is not possible to indicate which channel(s) attained boiling first. The heat fluxes for Locations 1, 2, and 3 are known from the

TABLE 1
SODIUM-BOILING TEST DATA
(Sheet 1 of 8)

	Run No.	Test Section Pressure (psia)	Test Section Inlet Temperature (°F)	Test Section Inlet Subcooling (°F)	Heat Flux (Btu/hr-ft ² 10 ⁶)			Bulk Superheat (°F)					Sodium Velocity (ft/sec)
					Heater 1	Heater 2	Heater 3	TC-1	TC-2	TC-3	TC-4	TC-5	
3A	A-1	4.91	1334	90	0.098	0.098	0.098	11	27	17	59	45	3.03
	A-2	4.89	1332	92	0.106	0.106	0.106	12	31	17	55	48	3.06
	A-3	5.04	1332	97	0.082	0.082	0.093	8	33	21	27	38	3.12
	A-4	4.93	1330	95	0.084	0.085	0.098	3	24	16	25	33	3.08
	A-5	5.00	1330	98	0.090	0.089	0.102	3	23	16	29	35	3.10
	A-6	4.89	1330	94	0.000	0.108	0.123	-49	34	22	6	8	3.15
	A-7	4.90	1329	95	0.088	0.089	0.100	4	25	19	27	41	3.08
	A-8	4.91	1329	95	0.000	0.096	0.110	-35	21	9	-12	-4	3.06
	A-9	4.90	1330	94	0.089	0.089	0.101	1	25	21	22	36	3.12
	A-10	4.91	1331	93	0.000	0.131	0.149	-13	82	58	18	24	3.12
	A-11	4.90	1332	92	0.102	0.097	0.110	26	51	39	51	60	3.03
	A-12	5.00	1331	97	0.103	0.105	0.119	22	57	43	44	61	3.15
	A-13	4.97	1331	96	0.086	0.086	0.098	9	31	19	30	39	3.12
	A-14	4.98	1330	97	0.098	0.099	0.113	21	55	42	50	68	3.10
	A-15	4.95	1330	96	0.090	0.090	0.103	8	34	22	33	45	3.08
	A-16	4.97	1330	97	0.090	0.091	0.103	-2	33	14	22	36	3.03
	A-17	4.92	1333	92	0.103	0.102	0.116	18	52	38	47	53	3.03
	A-18	4.90	1332	92	0.089	0.089	0.101	4	23	14	22	31	3.08
	A-19	4.90	1332	92	0.088	0.088	0.100	7	26	16	26	38	3.03
	A-20	4.98	1331	96	0.102	0.103	0.116	17	54	40	47	60	3.10
	A-21	4.89	1331	97	0.092	0.093	0.105	-4	21	11	22	31	3.15
	A-22	4.92	1331	94	0.093	0.091	0.104	6	27	16	25	36	3.10
	A-23	4.92	1331	94	0.104	0.103	0.118	14	51	37	49	45	3.10
	A-24	4.83	1332	87	0.088	0.088	0.100	14	43	28	36	43	3.15
	A-25	4.87	1331	92	0.095	0.095	0.108	17	53	40	46	56	3.10
	A-26	4.82	1332	90	0.083	0.083	0.094	3	24	13	23	24	3.12
	A-27	4.86	1331	92	0.088	0.088	0.100	5	27	18	29	30	3.12

TABLE 1
SODIUM-BOILING TEST DATA
(Sheet 2 of 8)

	Run No.	Test Section Pressure (psia)	Test Section Inlet Temperature (°F)	Test Section Inlet Subcooling (°F)	Heat Flux (Btu/hr-ft ² 10 ⁶)			Bulk Superheat (°F)					Sodium Velocity (ft/sec)
					Heater 1	Heater 2	Heater 3	TC-1	TC-2	TC-3	TC-4	TC-5	
3A	A-28	4.83	1331	91	0.081	0.081	0.093	8	33	20	29	32	3.15
	A-29	4.91	1331	93	0.088	0.085	0.098	15	44	26	36	36	3.12
	A-30	4.86	1330	93	0.094	0.093	0.106	12	29	19	34	38	3.08
	A-31	4.91	1331	93	0.095	0.093	0.107	20	50	37	48	55	3.12
	A-32	4.87	1333	90	0.106	0.104	0.119	28	58	45	54	69	3.12
	A-33	4.90	1335	89	0.083	0.083	0.094	10	33	22	29	39	3.10
	A-34	4.90	1336	88	0.077	0.078	0.088	4	29	18	23	37	3.12
	A-35	4.92	1336	89	0.088	0.088	0.100	10	34	23	28	42	3.12
	A-36	4.93	1336	89	0.098	0.095	0.108	24	61	48	47	62	3.15
	A-37	4.90	1336	88	0.087	0.086	0.099	17	43	31	37	49	3.10
	A-38	4.86	1336	87	0.110	0.106	0.123	33	70	57	60	81	3.08
	A-39	4.77	1338	82	0.091	0.088	0.101	16	35	26	29	42	3.15
	A-40	4.84	1336	86	0.110	0.106	0.123	35	67	54	54	64	3.12
	A-41	4.90	1335	89	0.085	0.081	0.095	3	33	20	23	19	3.10
	A-42	4.89	1334	90	0.103	0.099	0.115	24	64	43	44	54	3.12
	A-43	4.81	1333	88	0.095	0.091	0.105	22	58	43	39	46	3.12
	A-44	4.89	1333	91	0.103	0.099	0.115	26	69	52	47	53	3.10
	A-45	4.93	1332	93	0.113	0.110	0.126	29	69	52	49	62	3.10
	A-46	4.93	1332	93	0.103	0.101	0.116	19	56	42	40	60	3.12
	A-47	4.73	1332	87	0.083	0.080	0.092	1	30	17	23	17	3.12
	A-48	4.82	1333	89	0.102	0.099	0.114	26	63	46	43	53	3.10
	A-49	4.95	1334	92	0.104	0.101	0.117	29	76	54	51	55	3.12
	A-50	4.92	1334	91	0.082	0.080	0.092	2	28	16	12	24	3.12
	A-51	4.92	1334	91	0.089	0.085	0.098	11	43	26	17	24	3.10
	A-52	4.92	1335	90	0.084	0.081	0.093	8	39	20	16	24	3.08
	A-53	4.92	1335	90	0.109	0.104	0.120	22	69	49	39	48	3.12

TABLE 1
SODIUM-BOILING TEST DATA
(Sheet 3 of 8)

	Run No.	Test Section Pressure (psia)	Test Section Inlet Temperature (°F)	Test Section Inlet Subcooling (°F)	Heat Flux (Btu/hr-ft ² 10 ⁶)			Bulk Superheater (°F)					Sodium Velocity (ft/sec)
					Heater 1	Heater 2	Heater 3	TC-1	TC-2	TC-3	TC-4	TC-5	
3A	B-1	4.98	1234	193	0.151	0.158	0.152	10	22	10	19	47	3.12
	B-2	5.08	1234	196	0.143	0.148	0.148	-2	37	8	19	43	3.08
	B-3	5.16	1233	200	0.147	0.161	0.156	-6	43	17	22	51	3.08
	B-4	4.98	1234	193	0.145	0.154	0.150	-5	43	14	33	49	3.08
	B-5	5.00	1235	193	0.144	0.148	0.151	-3	37	9	16	48	3.12
	B-6	5.04	1235	194	0.137	0.143	0.140	-21	20	-3	2	20	3.08
	B-7	5.04	1236	193	0.146	0.157	0.153	5	44	16	28	58	3.10
	B-8	5.02	1237	192	0.148	0.156	0.153	8	42	17	17	46	3.12
	B-9	5.01	1238	190	0.139	0.148	0.145	-6	38	11	16	46	3.12
	B-10	4.91	1239	185	0.147	0.165	0.161	7	48	15	26	56	3.08
	B-11	4.96	1240	186	0.144	0.158	0.153	12	42	22	27	66	3.08
	B-12	4.97	1241	185	0.150	0.164	0.160	16	32	16	19	40	3.08
	B-13	4.74	1243	176	0.135	0.146	0.143	1	38	25	21	45	3.15
	B-14	4.80	1244	177	0.141	0.151	0.147	17	38	26	24	51	3.12
	B-15	4.88	1244	179	0.134	0.149	0.145	1	44	23	21	38	3.10
	B-16	4.89	1241	188	0.137	0.148	0.144	-7	32	19	9	34	3.08
	B-17	4.91	1239	185	0.141	0.154	0.150	-2	34	23	16	48	3.12
	B-18	4.88	1237	186	0.137	0.157	0.153	0	40	26	24	47	3.12
	B-19	4.89	1237	187	0.139	0.161	0.156	-4	40	31	20	40	3.12
	B-20	4.90	1236	188	0.138	0.151	0.147	-11	34	29	22	37	3.12
	B-21	4.70	1233	185	0.150	0.176	0.171	14	30	19	16	40	3.15
	B-22	4.75	1231	189	0.134	0.145	0.141	-30	29	12	18	50	3.10
	B-23	4.79	1230	191	0.143	0.158	0.153	-21	44	25	24	73	3.12
	B-24	4.78	1228	192	0.134	0.154	0.150	-41	39	7	23	54	3.12
	B-25	4.81	1227	194	0.147	0.171	0.166	-29	52	23	32	70	3.08

TABLE 1
SODIUM-BOILING TEST DATA
(Sheet 4 of 8)

	Run No.	Test Section Pressure (psia)	Test Section Inlet Temperature (°F)	Test Section Inlet Subcooling (°F)	Heat Flux (Btu/hr-ft ² 10 ⁶)			Bulk Superheat (°F)					Sodium Velocity (ft/sec)
					Heater 1	Heater 2	Heater 3	TC-1	TC-2	TC-3	TC-4	TC-5	
3A	B-26	4.85	1233	190	0.138	0.163	0.152	-15	27	7	19	62	3.08
	B-27	4.93	1231	194	0.129	0.162	0.152	-7	42	15	30	58	3.08
	B-28	4.80	1231	190	0.131	0.156	0.146	-15	47	18	34	43	3.10
	B-29	5.00	1232	196	0.136	0.159	0.149	-22	43	15	36	47	3.08
	B-30	4.86	1234	189	0.135	0.159	0.149	-6	36	13	27	59	3.08
	B-31	4.91	1236	188	0.131	0.156	0.147	-30	33	17	23	48	3.08
	B-32	4.92	1237	188	0.130	0.161	0.151	-29	40	16	35	62	3.06
	B-33	4.98	1239	188	0.135	0.160	0.150	-26	52	26	31	63	3.08
	B-34	5.06	1240	190	0.130	0.154	0.143	-29	50	17	30	58	3.12
	B-35	5.04	1240	189	0.128	0.160	0.150	-34	45	18	30	59	3.08
	B-36	5.00	1239	189	0.139	0.165	0.155	-5	49	22	36	60	3.08
	B-37	4.86	1237	186	0.129	0.152	0.142	-36	42	16	36	44	3.08
	B-38	4.98	1237	190	0.136	0.164	0.153	-29	44	18	31	61	3.10
	B-39	5.02	1234	195	0.138	0.165	0.155	-2	57	28	34	59	3.06
	B-40	4.92	1229	196	0.138	0.163	0.152	-28	53	25	38	67	3.12
	B-41	4.91	1227	197	0.130	0.161	0.151	-29	37	10	17	39	3.03
	B-42	4.89	1227	197	0.131	0.156	0.146	-24	36	11	18	51	3.08
	B-43	4.92	1228	197	0.134	0.166	0.156	-33	47	11	32	47	3.03
	B-44	4.95	1228	198	0.123	0.155	0.145	-36	39	8	17	29	3.03
	B-45	4.89	1228	196	0.129	0.161	0.151	-33	40	14	23	46	3.06
	B-46	4.86	1231	192	0.131	0.163	0.152	-31	38	13	28	50	3.06
	B-47	4.93	1232	193	0.130	0.165	0.154	-30	39	17	32	44	3.03
	B-48	4.88	1234	189	0.124	0.154	0.145	-33	37	9	18	35	3.06
	B-49	4.89	1234	190	0.133	0.158	0.148	-27	48	20	24	45	3.06
	B-50	4.90	1235	189	0.131	0.154	0.144	-24	45	19	29	49	3.06

TABLE 1
SCDIUM-BOILING TEST DATA
(Sheet 5 of 8)

	Run No.	Test Section Pressure (psia)	Test Section Inlet Temperature (°F)	Test Section Inlet Subcooling (°F)	Heat Flux (Btu/hr-ft ² 10 ⁶)			Bulk Superheat (°F)					Sodium Velocity (ft/sec)
					Heater 1	Heater 2	Heater 3	TC-1	TC-2	TC-3	TC-4	TC-5	
3A	C-1	4.85	1132	291	0.173	0.205	0.221	-8	5	20	0	9	3.10
	C-2	4.90	1132	292	0.178	0.201	0.217	13	16	55	12	7	3.10
	C-3	4.95	1132	294	0.179	0.216	0.233	12	18	43	4	7	3.12
	C-4	5.05	1132	298	0.180	0.206	0.222	16	12	52	11	-1	3.12
	C-5	5.07	1135	295	0.178	0.215	0.231	32	18	53	-15	-1	3.10
	C-6	5.09	1139	292	0.181	0.217	0.234	16	17	53	-8	5	3.06
	C-7	4.92	1146	279	0.164	0.193	0.208	21	14	49	-13	-4	3.06
	C-8	5.00	1146	282	0.172	0.204	0.220	43	30	70	15	10	3.03
	C-9	4.82	1146	276	0.166	0.191	0.206	25	15	52	-12	-3	3.08
	C-10	4.90	1146	278	0.186	0.218	0.235	57	43	85	12	18	3.08
	C-11	4.74	1145	274	0.179	0.204	0.220	58	36	77	14	9	3.03
	C-12	4.68	1142	275	0.173	0.197	0.213	32	21	57	-8	-1	3.01
	C-13	4.70	1139	279	0.171	0.191	0.206	30	13	49	-20	-14	3.06
	C-14	4.61	1136	278	0.174	0.202	0.218	27	16	46	5	-5	3.08
	C-15	4.74	1133	286	0.186	0.218	0.234	63	44	90	22	11	3.06
	C-16	4.80	1136	285	0.182	0.214	0.231	62	49	81	21	5	3.08
	C-17	4.88	1139	284	0.193	0.227	0.244	70	60	102	20	23	3.06
	C-18	4.86	1141	282	0.176	0.214	0.231	48	29	72	15	-5	3.08
	C-19	5.01	1143	285	0.186	0.221	0.238	71	44	98	15	10	3.08
	C-20	4.70	1140	278	0.174	0.206	0.222	36	23	54	-9	-4	3.10
	C-21	4.74	1138	281	0.173	0.210	0.226	35	31	52	-2	-4	3.15
	C-22	4.67	1135	282	0.175	0.201	0.218	34	20	53	11	3	3.08
	C-23	4.74	1132	287	0.171	0.202	0.218	33	17	57	12	-1	3.12
	C-24	4.81	1129	292	0.177	0.203	0.218	27	20	56	-15	-6	3.06
	C-25	4.88	1125	298	0.188	0.225	0.243	56	37	82	13	12	3.08

TABLE 1
SODIUM-BOILING TEST DATA
(Sheet 6 of 8)

	Run No.	Test Section Pressure (psia)	Test Section Inlet Temperature (°F)	Test Section Inlet Subcooling (°F)	Heat Flux (Btu/hr-ft ² 10 ⁶)			Bulk Superheat (°F)					Sodium Velocity (ft/sec)
					Heater 1	Heater 2	Heater 3	TC-1	TC-2	TC-3	TC-4	TC-5	
3A	C-26	4.72	1128	291	0.183	0.210	0.226	-8	8	46	-11	13	3.21
	C-27	4.74	1127	292	0.181	0.206	0.223	-32	9	53	-19	12	3.19
	C-28	4.77	1127	293	0.178	0.203	0.219	-43	9	49	15	14	3.15
	C-29	4.92	1128	297	0.196	0.235	0.254	-9	53	108	25	51	3.17
	C-30	4.91	1131	293	0.171	0.197	0.213	-56	4	53	-1	1	3.17
	C-31	4.83	1134	288	0.173	0.196	0.211	-57	3	53	-22	3	3.17
	C-32	4.77	1142	278	0.162	0.188	0.203	-72	-14	30	-27	-5	3.19
	C-33	4.80	1141	280	0.164	0.189	0.204	-54	8	59	10	5	3.15
	C-34	4.92	1140	285	0.186	0.227	0.246	-24	48	114	32	56	3.19
	C-35	5.08	1137	293	0.196	0.238	0.257	-18	73	130	57	71	3.12
	C-36	4.83	1136	286	0.168	0.194	0.210	-60	12	49	8	6	3.21
	C-37	4.82	1135	287	0.170	0.192	0.207	-69	1	29	-8	-2	3.15
	C-38	4.83	1136	286	0.173	0.199	0.214	-51	23	53	14	14	3.21
	C-39	4.82	1137	285	0.173	0.206	0.222	-52	20	49	14	17	3.17
	C-40	4.83	1139	283	0.166	0.193	0.207	-57	9	49	-4	7	3.12
	C-41	4.83	1138	284	0.178	0.206	0.222	-31	21	50	16	20	3.12
	C-42	5.00	1136	292	0.186	0.231	0.248	-17	53	105	43	63	3.15
	C-43	5.06	1133	297	0.195	0.235	0.253	-13	63	105	53	67	3.17
	C-44	4.81	1131	290	0.176	0.211	0.226	-56	23	57	17	12	3.19
	C-45	4.83	1130	288	0.175	0.205	0.221	-50	23	48	7	11	3.15
	C-46	4.80	1131	290	0.175	0.210	0.226	-44	22	45	5	13	3.15
	C-47	4.97	1133	294	0.192	0.234	0.251	17	66	107	50	59	3.15
	C-48	4.86	1134	289	0.170	0.201	0.216	-32	30	59	12	22	3.17
	C-49	5.03	1134	295	0.191	0.231	0.248	8	65	105	45	55	3.17
	C-50	5.17	1133	300	0.201	0.256	0.278	15	96	145	73	90	3.15

TABLE 1
SODIUM-BOILING TEST DATA
(Sheet 7 of 8)

	Run No.	Test Section Pressure (psia)	Test Section Inlet Temperature (°F)	Test Section Inlet Subcooling (°F)	Heat Flux (Btu/hr-ft ² 10 ⁶)			Bulk Superheater (°F)					Sodium Velocity (ft/sec)
					Heater 1	Heater 2	Heater 3	TC-1	TC-2	TC-3	TC-4	TC-5	
3A	D-1	5.04	1336	103	0.087	0.086	0.094	-36	-39	-36	-12		5.88
	D-2	5.46	1323	121	0.165	0.192	0.208	21	20	25	41		5.91
	D-3	5.65	1322	125	0.182	0.214	0.232	34	13	38	35		5.93
	D-4	4.62	1321	94	0.111	0.122	0.133	0	-3	0	18		5.91
	D-5	4.61	1323	91	0.083	0.091	0.098	-14	-18	-16	5		5.93
	D-6	4.67	1323	94	0.107	0.118	0.128	-1	-5	-1	23		5.95
	D-7	4.61	1322	92	0.091	0.100	0.109	-7	-11	-14	11		5.88
	D-8	5.66	1320	127	0.186	0.223	0.239	41	33	46	62		5.93
	D-9	4.50	1320	91	0.090	0.098	0.106	-14	-16	-11	10		6.00
	D-10	4.56	1321	92	0.107	0.118	0.128	1	-5	2	26		5.91
	D-11	4.55	1322	91	0.105	0.116	0.126	3	-1	4	21		5.91
	D-12	5.30	1323	114	0.167	0.193	0.208	39	29	43	75		5.91
	D-13	4.77	1323	98	0.115	0.126	0.137	0	-5	2	21		5.95
	D-14	5.63	1323	124	0.176	0.206	0.222	47	29	46	83		5.95
	D-15	5.22	1328	107	0.166	0.192	0.207	42	30	50	74		6.00
	D-16	5.01	1329	99	0.141	0.158	0.171	20	10	22	40		5.88
	D-17	4.65	1329	87	0.101	0.111	0.120	2	-6	3	20		5.91
	D-18	5.28	1329	107	0.159	0.183	0.197	43	29	45	75		5.91
	D-19	4.74	1329	90	0.087	0.095	0.103	-15	-25	-16	6		5.93
	D-20	5.63	1329	118	0.178	0.211	0.227	36	27	43	79		5.91
	D-21	5.12	1330	102	0.144	0.162	0.175	19	9	28	32		5.86
	D-22	5.26	1336	100	0.161	0.186	0.200	36	28	45	76		5.91
	D-23	4.80	1335	86	0.098	0.107	0.116	-5	-7	3	19		5.95
	D-24	5.29	1332	105	0.159	0.184	0.198	37	27	40	78		5.95
	D-25	5.53	1331	113	0.174	0.206	0.221	37	28	52	64		5.95

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TABLE 1
SODIUM-BOILING TEST DATA
(Sheet 8 of 8)

Run No.	Test Section Pressure (psia)	Test Section Inlet Temperature (°F)	Test Section Inlet Subcooling (°F)	Heat Flux (Btu/hr-ft ² 10 ⁶)			Bulk Superheat (°F)					Sodium Velocity (ft/sec)
				Heater 1	Heater 2	Heater 3	TC-1	TC-2	TC-3	TC-4	TC-5	
3A	D-26	4.90	1323	101	0.159	0.183	0.197	19	24	32	46	5.97
	D-27	6.00	1320	137	0.199	0.252	0.272	35	45	58	49	6.00
	D-28	4.77	1317	103	0.146	0.165	0.177	13	18	27	45	6.13
	D-29	5.02	1320	108	0.173	0.190	0.204	20	29	42	71	6.08
	D-30	5.17	1320	113	0.171	0.200	0.216	20	30	38	65	6.04
	D-31	5.73	1320	130	0.198	0.253	0.274	45	59	71	103	6.04
	D-32	4.50	1328	83	0.096	0.104	0.113	-8	-5	-1	13	6.06
	D-33	4.90	1329	95	0.152	0.176	0.189	23	32	42	65	6.08
	D-34	4.62	1328	87	0.106	0.111	0.120	-9	-5	1	15	6.11
	D-35	4.62	1326	89	0.105	0.116	0.125	-9	-5	2	16	6.09
	D-36	4.87	1327	96	0.157	0.182	0.196	25	33	41	63	6.06
	D-37	4.90	1328	96	0.157	0.183	0.197	29	37	47	66	6.09
	D-38	4.70	1329	89	0.119	0.133	0.143	-1	14	14	29	6.00
	D-39	4.91	1329	95	0.152	0.174	0.188	25	36	42	63	6.09
	D-40	4.59	1339	75	0.092	0.101	0.109	-6	-1	3	16	6.00
	D-41	5.40	1338	102	0.156	0.181	0.195	21	32	40	53	5.91
	D-42	4.76	1335	85	0.099	0.110	0.119	-14	-8	-6	8	5.95
	D-43	4.63	1333	82	0.099	0.110	0.119	-6	-2	4	20	5.91
	D-44	5.47	1334	108	0.165	0.193	0.208	23	33	41	49	5.95
	D-45	5.26	1334	102	0.151	0.173	0.186	18	28	35	43	5.97
	D-46	4.86	1334	89	0.118	0.132	0.143	-1	4	12	35	5.93
	D-47	5.49	1339	104	0.159	0.184	0.198	21	30	28	52	5.86
	D-48	5.07	1339	91	0.139	0.157	0.169	19	22	31	47	5.88
	D-49	5.06	1337	93	0.148	0.168	0.181	26	32	42	64	5.95
	D-50	5.06	1336	94	0.148	0.169	0.182	26	30	39	67	5.95

HEATER OD = 0.250 in.
 TEST SECTION ID AROUND HEATER = 0.357 in.
 THERMOCOUPLES ARE GROUNDED-JUNCTION,
 304-SHEATHED, 40-mil OD

Figure 1. Thermocouple Locations and Symbols

Figure 2. Group 3A Data Plot
(Run A1 through A53)

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respective power inputs to the pins; to maintain consistency with respect to heat flux the heat flux in Location 4 was taken as being the average of Pins 1 and 3, and for Location 5 (the center) the heat flux was taken as being the average of Pins 1, 2, and 3. The maximum and minimum measured superheats are shown to span the all-liquid prediction which is based on the same heat-loss/heat-flux as for a single pin. The maximum values are shared by Locations 2 and 5 whereas Location 1 contains the minimum values.

As discussed in more detail later, as inlet subcooling increases, the probability that boiling will not occur in certain channels increases.

Figures 3 and 4 show the Group 3A (B1 through B50) and Group 3A (C1 through C50) data, which are for 3 ft/sec and 190°F inlet subcooling and 285°F inlet subcooling respectively. In each case correspondence between the trends shown by the data and the all-liquid prediction is good. Bulk superheats of less than -15°F result in wall superheats of less than zero and thereby show that boiling was not possible for these points.* Except for one group (Figure 4) of readings,† Location 1 contains virtually all of the lowest superheats. The data of Figure 4 show very strongly the almost direct increase of superheat with heat flux for otherwise fixed conditions.

Data for test conditions of 6 ft/sec and 100°F inlet subcooling are shown in Figure 5 in terms of superheat vs heat flux. The trend shown by the all-liquid heat balance is seen to be in good agreement with the data. The most notable difference between these data and those for 3 ft/sec velocity in Figure 2, is that at the higher velocity each channel tends to be equally represented across the entire heat-flux range rather than being restricted to a certain range. This greater uniformity at the higher velocity may be the result of more thorough fluid mixing.

*If an all-liquid heat-transfer coefficient of about $10,000 \text{ Btu/hr/ft}^2 \cdot ^\circ\text{F}$ is assumed, a heat flux of $0.10 \times 10^6 \text{ Btu/hr-ft}^2$ will produce a 10°F difference between the wall and bulk temperature.

†As the three-pin heater was removed and then reinstalled after the first group of high-temperature readings, it is suspected that a shift in heater location occurred.

Figure 3. Group 3A Data Plot (Runs B1 through B50)

Figure 4. Group 3A Data Plot
(Runs C1 through C50)

Figure 5. Group 3A Data Plot
(Runs D1 through D50)

Despite the aforementioned improved uniformity of superheat distribution among various channels, Figure 6 shows the maximum superheat to be located in a particular channel both at 3 and 6 ft/sec. At the lower velocity the highest superheat is in the center channel (Location 5); at the higher velocity it is at 4 (between Pins 1 and 3). However, at 6 ft/sec the Location-5 thermocouple was not functioning.

C. PHASE-2 TOPICAL REPORT ON SINGLE-CHANNEL SUPERHEATING

A topical report entitled, "Effects of Velocity, Oxide Level, and Flow Transients on Boiling Initiation in Sodium," AI-AEC-12939 has been written in draft form. A brief summary of some of the information covered in this topical report was given in the Quarterly Technical Progress Report for October-December 1969, AI-AEC-12914.

D. THREE-CHANNEL TEST SECTION

The fabrication of a 30-in.-long three-channel test section is nearly complete. This will be similar to the 15-in. test section in that it will be fabricated with an instrumented flow-distributor insert inside of a primary container. It has been designed to accept a 15-in.-long three-pin heater, a 30-in. three-pin heater, and a specially constructed 30-in. three-pin heater. The last one will actually have only the lower 15 inches heated while the upper 15 inches will be unheated in order to hydraulically mock-up a section of blanket above the heated zone of a fuel pin.

E. THREE-PIN HEATER

Two 15-in.-long three-pin heaters have been fabricated and tested to destruction. The first heater had a life of 290 experimental tests. Failure of the heater was due to creep which allowed the molybdenum central electrode to settle down against the body resulting in a short circuit. At the time of failure, the graphite/boron-nitride part of the heater was still in excellent condition. The second heater had a life of 125 experimental tests. Failure of the second heater was due to vapor-blanketing of the sodium coolant which occurred at approximately a heat flux of $180,000 \text{ Btu/hr-ft}^2$ and a sodium velocity of approximately 0.1 to 0.2 ft/sec at 5 psia. This vapor-blanketing caused complete melting of the 304 stainless-steel sheath for several inches along two of the three heater pins.

Figure 6 Maximum Superheats at 3 and 6 ft-sec

The development concept of the three-pin heater is now considered to be adequate and only minor improvements are anticipated, such as providing more electrode-settling room to allow for creep.

F. UPGRADING PACKAGE

An "upgrading package" has been prepared in accordance with the program letter. This covers all modifications required to provide the forced-convection loop with seven-pin seven-channel experimental capacity. In support of the upgrading package two drawings have been made; piping and equipment location, and P&I diagram.

G. THEORY: CONVERSION OF TWO-PHASE STEAM CODES FOR USE WITH SODIUM

The topical report entitled "SODIFAZE a Steady-State Multichannel Boiling Sodium Code," AI-AEC-12804, was published February 15, 1970. Results obtained from the SODIFAZE code have been reported in previous quarterly reports.

H. THEORY: ANALYSIS OF THE STATISTICAL DISTRIBUTION OF INCIPIENT BOILING IN SODIUM

The topical report entitled, "Analysis of the Statistical Distribution of Incipient Boiling," AI-AEC-12906, was published December 31, 1969. A brief summary of this report was given in the Quarterly Technical Progress Report for October-December 1969, AI-AEC-12914.

IV. EVALUATION OF EFFORT TO DATE

Progress is considered to be satisfactory. Two hundred and twelve, three-pin three-channel liquid superheat tests were performed this quarter. These three-pin tests are probably the first multiple-pin superheat tests ever performed in sodium. The information from these and subsequent tests should help to provide a clearer understanding of in-core boiling conditions. A draft of the Phase-2 topical report on single-channel superheating was completed. This report provides new experimental information of the effects of velocity, oxide level, and flow transients on boiling-initiation in sodium. Two typical

reports were released; a report on SODIFAZE, AI-AEC-12804, and a report on the statistical distribution of incipient boiling, AI-AEC-12906. The SODIFAZE report provides the safety analysis engineer with a new analytical tool as well as some new insights concerning the safety margin available in the two-phase hydrodynamic flow region. The second report, a study of the statistical distribution of incipient boiling, demonstrates analytically that the upper superheating values obtained from the single-channel studies are very near the maximum that can be expected.

A 30-in.-long three-channel test section is nearly ready for installation in the forced-convection loop. This test section will allow a more exact mockup of an LMFBR fuel element, in that 30-in. heaters may be tested and that a 15-in. hydraulic mockup of the blanket area can be simulated with the use of a special 30-in. heater described in Section III-D. An "upgrading package" has been prepared in accordance with the program letter.

V. NEXT REPORT PERIOD ACTIVITIES

Hydrodynamic testing with the three-pin, three-channel test section will be started.

The Phase-2 topical report on the single-channel superheating data will be released as AI-AEC-12906.