278 + 120 FAST REACTOR DWR. 1635
A+B Formel

AI-AEC-12979

MASTER

QUARTERLY TECHNICAL PROGRESS REPORT
LMFBR SAFETY PROGRAMS
JULY - SEPTEMBER 1970

AEC Research and Development Report

Atoms International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

QUARTERLY TECHNICAL PROGRESS REPORT
LMFBR SAFETY PROGRAMS
JULY-SEPTEMBER 1970

The preceding Progress Report (Annual) was
AI-AEC-12970

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Atomics International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304

CONTRACT: AT(04-3)-701
ISSUED: NOVEMBER 12, 1970

DISTRIBUTION

This report has been distributed according to the category "Health and Safety" as given in the Standard Distribution for Unclassified Scientific and Technical Reports, TID-4500.

CONTENTS

<u>AEC Task No.</u>	<u>Project Title</u>	<u>Page</u>
6-D and E	Nuclear Safety, Gaseous Effluents, Sodium Fires	5
6-G	Nuclear Safety (Kinetics), Boiling Studies for Sodium Reactor Safety.	21

ERRATA
FOR
QUARTERLY TECHNICAL PROGRESS REPORT
LMFBR SAFETY PROGRAMS
JULY-SEPTEMBER 1970

AI-AEC-12979

Page 14, TABLE 3

Delete "gm" after 0.94 and 0.06.

Delete " μ Ci" after 0.90 and 0.10.

ATOMICS INTERNATIONAL
A Division of North American Rockwell Corporation

Program: Reactor Development

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

Project Manager: H. A. Morewitz

Reporting Period: July-September 1970

General Order: 07702

Subaccount: 31111

AEC Category: 04-60-40-02.1

Principal Contributors: R. L. Koontz, R. P. Johnson, C. T. Nelson,
L. Baurmash, J. E. Granger, J. Hopenfeld,
M. Silberberg, D. F. Hausknecht, E. U. Vaughn,
M. A. Greenfield

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 oxides, 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 FY 1971

A comprehensive review⁽¹⁾ of the HAA-3 aerosol model was published as AI-AEC-12977. Comparisons were made between model predictions and experiments which covered a volume ratio of 50 and a mass concentration up to 200 $\mu\text{g/cc}$. The agreement was good for four time-dependent parameters when the aerosol density was reduced to account for the fluffiness of agglomerate.⁽²⁾ The model has been used to establish leaked masses resulting from hypothetical LMFBR (FFTF) accidents.^(3,4)

Iodine vapor scavenging by sodium oxide particulates was shown to be strongly influenced by the presence of the normal dust concentration in air. The dust particles compete with the oxide for the iodine vapor. If the iodine is released into dusty air before the oxide then agglomeration occurs mostly between the iodine-dust and oxide rather than between iodine and oxide.

Leakage of aerosols through cracked concrete has been shown to be substantially less than that which is assumed in most site safety studies. The aerosol mass is attenuated by 10^5 as it leaks through 1-1/2-in. -thick porous noncracked concrete.

III. PROGRESS DURING REPORT PERIOD

A. PUBLICATIONS

A topical report, AI-AEC-12977 (1970), "Aerosol Modeling of Hypothetical LMFBR Accidents," by R. L. Koontz, L. Baurmash, M. A. Greenfield, C. T. Nelson, D. F. Hausknecht, E. O. Vaughan, M. Silberberg, and H. A. Morewitz, was published.

Four papers were presented at the USAEC-Air Cleaning Conference in Richland, Washington, August 31 to September 3, 1970. The papers are (1) "Characterization of Energy Release and Aerosol Behavior From Sodium Spray Fires," J. Granger, C. Nelson, and M. Silberberg, (2) "Behavior of Iodine in the Presence of Sodium Oxide Aerosols," L. Baurmash, C. Nelson, J. Granger, and R. Koontz, (3) "Measurements of Particulate Filtration Efficiencies of Building Materials," C. Nelson, J. Granger, R. Koontz, and L. Baurmash, and (4) "Comparison of Aerosol Experiments to Models Used in Reactor Siting Evaluation," M. Greenfield, R. Koontz, R. Johnson, and H. Morewitz.

A paper entitled "Approximation Solution of Equations for Aerosol Agglomeration," by E. Richard Cohen and Edward U. Vaughan has been submitted to the J. of Colloid and Interface Science for publication.

B. AEROSOL LEAKAGE THROUGH CONTAINMENT BARRIERS

Particulate filtration by building materials is being studied to determine the attenuation of an aerosol source leaking from an enclosure as it passes through

leak paths in concrete or other porous material. Assuming (1) the cell or building envelope is composed of an internal welded steel liner plate surrounded by reinforced concrete and (2) all penetrations (bellow seals, potted joints, mechanical seals, O-rings, etc.) have provisions for individual testing and do not leak, the attenuation factor for sodium oxide aerosol can be as great (or greater) than 10^5 as it passes through leak paths in the liner and concrete. It has been shown⁽⁵⁾ that cracks seldom penetrate more than 50% of the wall thickness for properly designed reinforced structures during loading stresses. Under these conditions, preliminary experimental data indicate the sodium oxide particulate penetration may be limited (see Table 1).

The concrete test specimens were prepared using ready-mix concrete (design mix unknown) placed in a 2-in. pipe and the periphery sealed to the pipe wall with epoxy. Measurements were made of the airflow rates through the specimens at various pressure differentials to determine the effective crack width for each of the fractured test specimens. The aerosol filtration experiments were performed during the sodium oxide, iodine plus Na_2O , and uranium oxide aerosol experiments which are currently in progress. All aerosols which penetrate the specimen are captured on a membrane filter. The total gas flow through each specimen is measured during the test.

The results of the preliminary aerosol filtration experiments with concrete (Table 1) show that the reduction factor for sodium oxide varies from 10^3 (Specimen 3b) to $>10^5$ (Specimen 1). Specimens 2b and 2c show a reduction of about 70 and 400, respectively, for UO_2 aerosol. Approximately 45 mg of UO_2 was collected by Specimen 2b causing a reduction of flow rate of 10.5 to 1.8 l/min. During Test 2c, 30 mg of UO_2 was collected causing a reduction of flow rate of 1.8 to 0.4 l/min. Further tests of the same specimen will indicate the quantity of material required for complete clogging.

It is interesting to note the similarity in the reduction factor for Specimens 6b and 2b although the size and character of the crack in each test were dissimilar. This indicates impaction is an important particulate removal mechanism for relatively high flow rates.

Impactor samples were taken of the UO_2 aerosol used in the Specimen 2b filtration experiment. The upstream median size of the particles was greater than 3 microns in diameter ($\sigma = 2.9$) and the size of the particles which penetrated through the crack ranged between 0.3 and 1 micron in diameter (none smaller and none greater were observed).

TABLE 1
EXPERIMENTAL TEST DATA

Parameters	Concrete Specimens						
	6b	2b	2c	7	3b	5	1
Diameter (in.)	2	2	2	10	2	2	2
Thickness (in.)	2	1.5	1.5	1.37	1.5	1.5	1.5
Initial flow at 5 psig (l/min)	0.045	10.5	1.8	0.5	24	1.3×10^{-3}	1.2
Flow at 5 psig after test (l/min)	0.033	1.8	0.4	0.5	1.0	10^{-4}	1.2
Duration of test (minutes)	1440	4	20	60	4	1440	8
Type of leak	Crack [§]	Crack ^{**}	Crack [*]	Porous	Crack ^{**}	Porous	Crack ^{**,*}
ΔP across specimen during test (psig)	3	3 to 5	3 to 5	3 to 5	2.5 to 3	3	0.5
Crack width (mil) (initial and final)	0.47 to 0.42	4.4 to 2.1	2.1 to 1.3	None	4.9 to 1.7	None	1.8
Reduction ^{††} factor for sodium oxide	-	-	-	-	10^3	5×10^3 [†]	10^5 [†]
Reduction ^{††} factor - uranium oxide	70	71	400	3.5×10^3	-	-	-

*Previously reported

†Limit of detection

§Very rough surface (typical cracked concrete)

**Smooth surface (void between concrete and steel pipe - simulates a bond rupture between steel liner and concrete)

††Ratio of sodium oxide or uranium oxide entering concrete to that on membrane filter

Preliminary data indicate that thick concrete without cracks can act as an absolute filter for aerosols and it is reasonable to assume that any molecular sized particles which are attached to the aerosols are also removed by this filtration. There is some indication that the molecular sized particles can also be removed by filtration since these small particles have great diffusivity and are readily attached to any available surface. An investigation reported by A. W. Sanders, et al,⁽⁶⁾ shows that diffusion is the mechanism primarily responsible for the deposition of these small particles and that retention efficiency can approach 100% at low air flow velocities for even the poorest of filters.

The characterization of concrete structures as filtering media for the released aerosol material resulting from hypothetical accidents in LMFBR's is extremely important for reactor siting considerations, since it provides a large degree of conservatism in present models which assume aerosols behave as gases in passing through containment leaks. It is anticipated that further studies will show that effluents generated during a hypothetical accident will have a retention period in the concrete of hours or days.

C. SPRAY FIRE EXPERIMENTS

Two additional spray fires were performed during the report period; both were in reduced oxygen (10 to 5 mole %) environment with lowered humidities. The results of these tests (Table 2) indicate that there is a strong dependence of burning rate on the initial oxygen content for dry conditions but only slight dependence at high humidities. Figure 1 is a plot of the sodium fraction oxidized vs oxygen content for two humidity levels for all tests to date. The mechanism by which water vapor accelerates the oxidation mechanism is unknown but is under study and is expected to alter the temperatures (and vapor pressure) of the burning droplet.

A measured mean droplet diameter for the previous nozzles (0.065-in. swirl full cone) was reported in the preceding progress report⁽⁷⁾ to be $\sim 350 \mu$. Although measurement of the droplet size for the 0.028-in. capillary jet has not been possible, experimental correlation is available⁽⁸⁾ and predicts the same size range ($\sim 400 \mu$ m median size). The correlation is:

$$D_P = 36(D_N)^{0.56} (Re)^{-0.10}$$

7702-45239

Figure 1. Efficiency of Sodium Consumption as a Function of Oxygen and Water Content

TABLE 2
SPRAY TEST VESSEL - SPRAY FIRE SUMMARY

Spray Test No.*	Oxygen in Vessel (%)	Sodium Sprayed During Fire (gm)	Sodium Consumed During Fire (gm)	Sodium (Consumed/Sprayed)	Moles of Sodium Ejected/Moles O ₂	Sodium Reacted as Monoxide (%)	Observed $\Delta P/\%$ O ₂ (psig)	Oxygen Used During Spray (%)	Peak Spray Temperature in Flame Zone (°F)	Spray Duration (sec)	Initial Dew Point (°F)	Nozzle Type and Size (inils)	Sodium Spray Rate (gm/sec)	Sodium Consumed (gm/sec)	Initial Vessel Pressure, P ₁ (psia)	Measured Maximum Pressure Rise, ΔP (psig)	Computed Adiabatic Pressure Rise, ΔP (psig)
7	21	78.0	31.3	0.407	0.438	30	13.6	1.17	1300	7.0	~23	Swirl Full Cone (55)	11	4.5	17.7	15.9	25.7
9	2	100.8	36.3	0.360	5.95	0	11.3	2.03	952	4.6	~45	Swirl (55)	21.6	7.9	16.2	22.9	34.0
10	2	68	22	0.350	9.95	-	10.9	1.18	827	4.5	High	Swirl (55)	15.0	4.9	17.7	17.0	27.5
11	2	166	2	0.012	6.31	-	68.5	0.090	454	10.2	8	Swirl Full Cone (55)	16.3	0.2	17.6	6.17	~8
Series 1																	
AH	21	130	55	0.421	0.542	25	6.45	~2.2	950	16.5	43	28-mil jet	7.9	3.35	19.7	14.2	34.4
AL	21	181	52	0.290	0.756	0	4.30	2.7	760	27.5	-28	28-mil jet	6.9	1.91	19.7	11.6	39.5
B	10	152	18.3	0.12	1.42	14	10.7	0.75	580	22.5	-30	23-mil jet	6.85	0.81	19.7	8.0	16.1
C	5	158	49	0.32	2.80	3	7.25	2.2	720	22.5	~5	24-mil jet	6.97	2.21	19.3	10.4	33

*In all tests the initial temperature of the sodium was 1000°F and the spray pressure was ~50 psig.

AI-AEC-12979
11

7702-45229

Figure 2. Air Concentration for Particulate Iodine-Sodium Oxide System

where

D_P = diameter of particle (μm)

D_N = diameter of nozzle (μm)

Re = Reynolds number.

These droplet sizes are similar to those expected for pinhole leaks while the spray geometries for both impinging and free jets are represented in the tests described above.

Burning rate data obtained for sodium sprays in a 21% oxygen environment with both types of nozzles show good reproducibility.

D. LTV EXPERIMENTS

The Large Test Vessel (LTV) was readied for the forthcoming uranium and sodium aerosol modeling experiments by making system improvements.

The overall leak rate of the vessel, 3%/day, has been reduced with the addition of sealant material on all system connections. Post-test cleanup of the LTV has been enhanced by coating the interior of the vessel with a contamination resistant epoxy paint. The coating will reduce the time required for cleanup after a single or series of uranium or sodium aerosol experiments. Sampling tubes and automation instrumentation have been centralized and checked out.

E. LTC EXPERIMENTS - FISSION PRODUCT SIMULANTS

A second experiment was performed in the Laboratory Test Chamber (LTC) to study the agglomeration characteristics of iodine vapor on sodium oxide aerosols. A 660 μCi quantity of radiiodine-131 was released into the LTC and allowed to condense on Aitken nuclei which are normally present in air. In the previous test, the air in the chamber was recirculated through a millipore filter in order to remove the nuclei. After releasing the iodine into the chamber only 2 to 3% of the total activity was unagglomerated, found on charcoal filters which collect elemental iodine, (see Figure 2), as compared to 70% in the first test when the elemental iodine was released into a clean air environment.⁽⁷⁾ During the time period before the oxide was released, the concentration decreased with a half-time of about 100 min (400 min for Test 1). Immediately after sodium oxide was released (peak concentration of $6.4 \mu\text{g}/\text{cm}^3$), the initial radioactivity decayed with

a half-time of 10 min. The initial sodium oxide half-time was ~15 min. The initial half-time was 60 min for both mass and activity in the first test (peak sodium oxide concentration of $0.77 \mu\text{g}/\text{cm}^3$), by collection and measurement on millipore filters. The activity collected on the charcoal filters which were in series with the millipore filter did not decrease markedly during the time that the oxide and scavenged iodine was decreasing. After 2 hr, the charcoal or non-particulate fraction was the predominant airborne component. The particle size of both the radioiodine and sodium oxide grew to a maximum aerodynamic equivalent diameter (AED) of 7.0, 40 min after the release of sodium oxide. The AED was 1.6 immediately after the release of sodium oxide. Table 3 shows the mass balance for Test 2.

TABLE 3
MATERIAL BALANCE OF SODIUM AND IODINE-131 (Test 2)

	Sodium	Iodine-131
Total	7.23 gm	660 μCi
Fraction on Floor	0.94 gm	0.90 μCi
Fraction on Wall	0.06 gm	0.10 μCi

F. ANALYTICAL DEVELOPMENT

1. Aerosol Model for Scavenging of Molecular Species

Preliminary experiments conducted at Atomics International have indicated that molecular iodine is effectively scavenged by particulate aerosols of sodium oxide. Predictability of the rate of this type process in an accident analysis application is essential for estimating site requirements. A simple model has been proposed, which can be readily included in the existing framework of the moments method with the log normal approximation solution (HAA-3 computer program) of the aerosol equation.

The primary removal mechanism will be taken to be agglomeration, but condensation could be readily added later. The rate of change of the molecular concentration $M_v(t)$ of molecules of size v is then given by the collision rate,

$$\frac{dM_v(t)}{dt} = -M_v(t) \int_0^\infty n(v',t) K(v,v') dv' \quad \dots (1)$$

where $n(v,t)$ is the aerosol number concentration at time t and $K(v,v')$ is the collision probability for aerosol particles and molecules which will be discussed more fully below. The molecular species concentration has been defined with the size v being a parameter. This is appropriate since a specific size can be associated with a species, such as I_2 , while in contrast, the aerosol distribution approaches a continuous function, $n(v,t)$. Knowledge of $n(v,t)$ which is evaluated by HAA-3, enables the solution of Equation 1.

The collision probability kernel, $K(v,v')$, is composed primarily of the effects due to Brownian motion, gravity, and possibly turbulence as in the case of aerosol agglomeration. However, in the present application one of the colliding particles is much smaller than the other. For such highly dispersed suspensions the theory for collisions due to Brownian motion must be corrected for the steep decline in small particle concentration within a few mean free paths (m.f.p. of the smaller particle) from the surface of the larger particle.

Computation of collision rates based on Smoluchowski's approach assumes the suspending medium is a continuum and no account is taken of kinetic gas theory. Consequently for particles as small as molecules, the collision rate is not proportional to $r^{1/2}$, which is predicted from kinetic theory. Several attempts have been made to correct the diffusion model for kinetic theory effects.⁽⁹⁻¹¹⁾ Also, extension of kinetic theory to particles larger than molecules has been tried.⁽¹²⁾ The most successful technique is due to Fuchs.⁽¹¹⁾

Fuchs suggests that around a colliding particle a spherical envelope exists within which there is a rapid change in particle concentration. The thickness of the envelope is the order of the apparent mean free path of particles. Kinetic gas theory is applied within the envelope and diffusion theory outside. Continuity of particle concentration and current is required at the envelope's surface.

As r_1 and r_2 approach molecular size ($r_1, r_2 \rightarrow 10^{-4} \mu m$), $K \rightarrow 2 \sqrt{2\pi} r^2 \bar{G}$, which is the expression as calculated from the well-known formula for the number of collisions between gas molecules where $G = 8KT/\pi m_i = brT/\pi^2 \rho r_i^3$.

Evaluation of the equation of the model,

$$\frac{dM_{v_1}(t)}{dt} = -M_{v_1}(t) \int_0^\infty n(v_2, t) [K_{BM}(v_1, v_2) + K_G(v_1, v_2)] dv_2 \quad , \quad \dots (2)$$

where

K_{BM} = Brownian motion collision probability and

K_G = gravitational collision probability

can be incorporated in the existing moments method computer program HAA-3. When the integral is evaluated numerically by dividing the range into discrete segments, the contribution from each segment is proportional to the activity deposited on particles with sizes within the segment.

2. Aerosol Collision Mechanisms

The behavior and relative importance of aerosol collisions arising from Brownian motion and gravity has been studied to provide an explanation for the observed growth of large particles of less than theoretical density. Growth of particles with radii up to 0.5μ has been shown to be due principally to Brownian motion, while particles with radii greater than 2.0μ result primarily from gravitational agglomeration. The strong preference of Brownian motion, for causing collisions between particles of widely dispersed sizes, has been identified as the reason for the narrowing of a distribution as it approaches the "self-preserving" form. Additionally, the study has suggested some particle size regimes where approximations of the kernel are appropriate. These approximations could lead to simpler computational schemes for the aerosol equations.

3. Spray Fire Modeling

The possibility of an occurrence of sodium fire due to pipe rupture or a release through a reactor head penetration or access port presents the most severe constraint on the design of LMFBR vaults and primary containment. Because a rigorous model for predicting the pressure rise in a cell as a result of a spray fire is not available at the present time, the severe constraints imposed on the designer are largely a result of upper limit methods of calculations.

Since the number of parameters which govern the energy release from a spray fire is very large, it will not be practical to conduct experiments which cover the entire range of all parameters which affect the energy release from sodium sprays. As an alternative approach, efforts have been recently initiated to develop a theoretical model of sodium spray burning and test its validity under experimentally controlled conditions. Previous models for computing sodium spray burning parameters were reviewed and found to be inadequate.

The starting point for the development of the sodium spray burning model is the equations for predicting the burning constant for single droplet combustion. The single droplet model adopted here is very similar to the classical model of liquid droplet burning. It differs from the latter in that the droplet is surrounded by two combustion zones instead of the one combustion zone usually considered. This modification was dictated by the observation that Na_2O_2 is the major reaction product. The temperature of the flame zone is considerably higher than 1700°F , however since Na_2O_2 is not stable at these temperatures it must form at some distance away from the flame zone. Figure 3 shows the essential features of the droplet model. It consists of a liquid sphere and three concentric mathematical surfaces which represent the first reaction zone where the intermediate products Na_2O are formed. The second reaction product Na_2O_2 is formed in an ambient zone which represents conditions at some distance from the droplet surface. In Reaction Zone A, sodium vapor is transferred by convection and diffusion toward the first reaction zone boundary. In Reaction Zone B, oxygen is transferred toward the reaction zone boundary, while the solid Na_2O aerosols are transferred in the opposite direction toward the second reaction zone boundary. In Reaction Zone C, water vapor and oxygen move toward the reaction zone boundary while Na_2O_2 and NaOH move in the opposite direction.

Effort to date has been directed toward setting up the equations which describe the simultaneous heat and mass transfer during droplet burning, and/or cooling if no oxygen is present.

This model will predict the chemical and thermal energy release characteristics of a sodium spray of known mean droplet size and will be scalable to permit its use for engineering application to accident analysis. Estimation of the crucial degree of subdivision and dispersion of a potential leak is a hydrodynamics problem which must be solved for each accident before using the new droplet model.

4. SOFIRE II Studies

During this report period the SOFIRE II code was used to calculate accident consequences to sodium test facilities resulting from various sodium spills in an air atmosphere and pool configuration. The objective of these analyses was to determine the burning time and characterize floor node temperatures resulting from these potential open fires. Various floor geometry configurations were

7702-4539

Figure 3. Droplet Model for Calculating Burning Rate Constant

considered: both normal concrete and a steel liner separated from the concrete by a nominal air gap. From these studies, it was shown that a steel liner and an air gap could reduce the concrete surface temperature rise resulting from potential sodium spills. However for large spills, insulation (fire brick, perlite concrete, etc.) is still required to minimize the potential for concrete damage.

IV. EVALUATION OF EFFORT TO DATE

Continuing progress is being made in developing experiments and improving modeling techniques which predict the consequences of hypothetical LMFBR accidents. These models can be used to evaluate the effect of postulated accidents on building pressures, liner and concrete temperature, and leakage of aerosols.

V. NEXT REPORT PERIOD ACTIVITIES

The Large Test Vessel (LTV) will be used to study UO_2 aerosols and sodium oxide aerosols. Continued aerosol and spray model improvements will be made.

A new series of spray fires will be conducted to provide a basis for development.

REFERENCES FOR TASK 6-D AND E

1. R. L. Koontz, et al, "Aerosol Modeling of Hypothetical LMFBR Accidents," AI-AEC-12977 (August 31, 1970)
2. W. R. Lane and B. R. D. Stone, "Structure and Density of Particulate Aggregates," Int. Conf. on Mechanisms of Corrosion by Fuel Impurities, Butterworths (1963)
3. J. Hale, "FFTF Site Safety Analysis," BNWL-1350 (1970)
4. "Final Report on FFTF Head-Cavity Study by the ANL Task Force," (August 1970) unpublished
5. C. Nelson, A. Gibson, and R. Koontz, "Prediction and Control of Leakage Through Cracks and Capillaries in Re-enforced Concrete Buildings Used to House Reactors," NAA-SR-Memo-9429 (1964)
6. A. W. Sanders, et al, "The Filtration of particles of Atomic Dimensions," NRL Report 7047 (1970)
7. "Annual Technical Progress Report, LMFBR Safety Programs, GFY 1970," AI-AEC-12970 (August 1970)
8. J. A. Duffle and W. R. Marshall; Jr., "Factors Influencing the Properties of Spray Dried Materials," Chem. Engr. Prog., 49, No. 8, 417 (1953)
9. S. K. Friedlander, J. Meteor., 18, 753 (1961)
10. G. Zebel, Kolloid-Z., 157, 37 (1958)
11. N. A. Fuchs, The Mechanics of Aerosols, translated by R. E. Daisley and Marine Fuchs, pp 290-295, Pergamon Press (New York 1964)
12. G. M. Hidy and J. R. Brock, J. Coll. Sci., 20, 477 (1965)

Program:	Fast-Reactor Development		
AEC Task:	6-G, Nuclear Safety (Kinetics), Boiling Studies for Sodium Reactor Safety		
Project Manager:	H. A. Morewitz		
Reporting Period:	July-September Quarterly Report, 1970		
General Order:	7702	Subaccount:	13410
		AEC Category:	04-60-01-09.1

Principal Investigators: D. Logan, J. Landoni, and C. Baroczy

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, fuel-meltdown accidents, and the ultimate shut-down 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 FY 1971

A tantalum-clad, high flux electrical heater, which can operate under continuous boiling conditions with sodium at 1400°F, was developed. Use of a 3-pin cluster of these heaters permitted the experimental determination of a sodium "check-curve" for a group of interconnected channels.

Analytical work now in progress shows that the decreasing trend of incipient wall superheat with increasing velocity is in correspondence with the kinetic energy of the eddies produced by turbulent flow.

III. PROGRESS DURING REPORT PERIOD

A. TWO PHASE THERMAL HYDRAULICS

Using the tantalum-clad heaters, described in Section III-B, in a 3-pin cluster, steady boiling sodium tests were performed to obtain the pressure drop - flow characteristics ("check curve") of the 3-channel test section. A cross section of the test section and the thermocouple locations are shown in Figure 4. The heaters are 15 in. long with a flat heat flux profile. The differential pressures are measured both across the heated portion of the channel and the upper one-third of the heated portion.

Figure 5 shows the check curve obtained by holding total heater power constant at about 12 kw and gradually increasing sodium flow rate. One test point

10-14-70 UNCL

6507-4736

Figure 4. Thermocouple Locations

7702-4746

Figure 5. Check Curve for 3-Channel Test Section

was obtained every 6-1/2 sec. During the run, the power to each heater was held constant, but not equal, as the highest power heater (No. 3) had about 25% greater power input than the lowest power heater (No. 1).

The gross check-curve characteristic shown in Figure 5 is as expected: in the all-liquid region, pressure drop decreases as flow decreases; in the boiling region, pressure drop increases as flow decreases. In the boiling region, point values of pressure drop are shown; actually, a vertical band of pressure drop exists at each flow rate. In addition, distinctive sub-regions are evident as identified by letters on the check curve. The basis for identifying the various regions is the fluid temperature in the various channels. Fluid temperatures for typical runs are given in Table 4. In the all-liquid

TABLE 4
CHANNEL TEMPERATURES

Thermocouple Location Region↓	Temperature (°F)					
	1	2	3	4	5	T _{sat}
ab (All-Liquid)	1318	1353	1422	1403	1408	1412
cd (Boiling Initiation)	1379	1446	1501	1499	1448	1435
de (Partial Boiling)	1399	1447	1444	1426	1433	1431
ef (Full Boiling)	1421	1413	1413	1410	1410	1414

region (ab), the fluid temperatures in the channels are close to, or below, saturation. In the boiling initiation region (cd), the channel temperatures range from below saturation (No. 1) to considerable liquid superheat (No. 3, 4). In the partial boiling region (de) the channel temperatures may be below (No. 1), above (No. 2, 3), or at (No. 4, 5) saturation; at the latter locations boiling is presumed to be occurring. In the full boiling region (ef), the channel temperatures are essentially equal to one another and to saturation, indicating boiling in all channels.

Although further confirmation is required, the present data (partial boiling region) indicate that it is possible for subcooled liquid, superheated liquid, and boiling liquid to coexist in a geometry consisting of interconnected channels. This observation must be qualified, however, because in the partial boiling region, pronounced fluid temperature fluctuations exist and the periodic (every 6-1/2 sec), rather than continuous, recording of every temperature presents a limitation. From the two continuous fluid temperature traces (Thermocouple No. 1, 2), it appears that fluid temperature fluctuations are small in Channel 2 as compared to Channel 1. In addition, in both channels, the temperature fluctuations are small in the full boiling region compared to the partial boiling region.

Comparison of the experimental check curve (Figure 5) with that predicted by the SODIFAZE code was made. However, a direct comparison between experiment and prediction was not possible for the following reasons: (1) At the present time the SODIFAZE code covers the range 1600 to 2000° F and hence does not predict a check curve for 1400° F. As a result, the code prediction at 1600° F (Figure 6) serves only to give a general idea of the check curve shape. (2) The predicted check curve is based on equal input power to each heater whereas in the experiment the heater powers differed by 25%. (3) The predicted check curve is based on the assumption that the three annular channels are identical in geometry and, as a result, the fluid enthalpy rise will be equal in each channel with equal heater input power. However, it appears that the annular clearance for Heater No. 1 is greater than for the other heaters because the liquid sodium temperature rise (in Channel 1) is much less than would be expected on the basis of the known difference in heater input power. For example, the fluid temperature rise, between the hottest and coldest channel, should differ by about 25% whereas it actually differs by more than a factor of two.

Figure 6 shows the check curve predicted from SODIFAZE to have a slight flat region during the period when each channel successively attains boiling. Channel 4 starts to boil first with a slight increase in pressure drop. As flow is further reduced, boiling then starts in Channel 5 with virtually no increase in pressure drop. Only when Channels 1, 2, and 3 attain boiling does the pressure drop increase rapidly. Additional experiments are required to establish the existence of the predicted flat portion of the check curve.

7702-4747

Figure 6. Predicted Check Curve for 3-Channel Test Section

B. THREE-PIN TANTALUM SHEATHED HEATER

A special heater cluster, consisting of three tantalum sheathed heaters, was fabricated for use in performing the two-phase thermal hydraulic tests. The cluster lasted for 156 minutes of testing of which more than 50% was with continuous boiling. Even so, the heater failure was associated with major vapor blanketing (indicated by maximum signals from the differential pressure and absolute pressure instruments).

For the check curve described in Section A, the heater operated under continuous boiling conditions at 1-1/2% mixture quality which was equivalent to 95% void fraction. Testing had to be performed without the aid of heater protective devices since all our protective devices are triggered by the onset of boiling.

C. BOILING INITIATION THEORY

1. Introduction

The minimum work $W_{\min}$ required to create a nucleus of the missing phase in a metastable phase, which will not collapse, can be expressed by the change in the thermodynamic potential Ω . This is because the temperature and the chemical potential of the nucleus and the surrounding medium are the same. Since no change of volume occurs when the nucleus is formed, the thermodynamic potentials before and after the formation of the missing phase are as follows:

$$\text{Before} \quad \Omega_{\ell} = -p(V + V') \quad (\text{metastable liquid phase only})$$

$$\text{After} \quad \Omega_{\ell+v} = -pV - p'V' + \sum_i \sigma_i A_i \quad (\text{both phases})$$

where $V + V'$ is the volume of the system (primed and unprimed parameters refer to the vapor and liquid, respectively), p is the absolute pressure, σ_i is the surface tension coefficient in correspondence with the interface A_i . Before the nucleus appears, $V_{\ell} = V + V'$, the whole volume is occupied by the metastable liquid; but after the nucleus appears

$$V_v = V'$$

$$V_{\ell} = V$$

In consequence,

$$W_{\min} = \Omega_{\ell+v} - \Omega_{\ell} = - (p' - p)V' + \sum_i \sigma_i A_i, \quad \dots (1)$$

expresses the required minimum work for the conditions specified on the right-hand side, i.e., the superheat $p' - p$, the volume of the nucleus (vapor bubble) V' and the interface contributions by the terms of the form $\sigma_i A_i$.

2. Surface Effects

For spherical bubbles in an unbounded medium (i.e., in absence of surface effects) the summation of terms on the right hand side of Equation 1 reduces to only one: σA , where A is the spherical surface enclosing the volume V' of the nucleus.

The Laplace formula provides the connection between the differential pressure and the radius a of the spherical bubble by

$$p' - p = \frac{2\sigma}{a}. \quad \dots (2)$$

Inserting the Laplace formula (2) into Equation 1, in order to eliminate the radius of the sphere, it renders

$$W_{\min} = \frac{16}{3} \pi \frac{\sigma^3}{(p' - p)^2}. \quad \dots (3)$$

It was indicated⁽¹⁾ that the same form for the minimum work can be preserved when the formation of the incipient bubbles occurs at the surface of the container, if σ is substituted by σ_e , an effective surface tension coefficient, that is

$$\sigma_e = f\sigma. \quad \dots (4)$$

Obviously for an unbounded medium

$$f = f_{\infty} = 1, \quad \dots (4')$$

while for perfectly flat surfaces⁽²⁾

$$f = f_o = \left(\frac{1 + \cos \beta}{2} \right)^{2/3} (2 - \cos \beta)^{1/3} \quad \dots (4'')$$

where β is the contact angle (Figure 7A).

For bubble formation at the vertex of a regular conical cavity (Figure 7B)

$$f = f_c = \frac{1}{2^{2/3}} \left(2 - 3 \cos \theta_o + 3 \cos^3 \theta_o + \frac{\sin^3 \theta_o}{\tan \theta_c} \right) \quad \dots (4''')$$

where the angle θ_o is related to the contact angle β , and the half-aperture of the cone θ_c by

$$\theta_o = \frac{\pi}{2} + \theta_c - \beta .$$

The behavior of f as indicated by Expressions 4'' and 4''' was shown in Reference 1 (Figures 34 and 35 at p. 67 and 68, respectively). Expression 4''' is of particular interest for the LMFBR situation, because the cavity sites, produced on the heat transfer surface by the corrosive action of the flowing sodium, are regular cones of about the same height and diameter. This implies a half aperture angle of about $26-1/2^\circ$.

3. Turbulent Flow Before Boiling Initiation

When turbulent flow prevails in the metastable liquid sodium (superheated sodium) before boiling inception, the detected superheats are relatively modest and remotely distant from those expected in the range predicted by the reduced van der Waals equation.*

Table 5, which was used for Figures 10 and 14 of Reference 3, indicates the wall superheat range of the experimental determinations, all of them at about 5 psia. The reported superheat ranges in Table 5 are not only far below

---

*An informal document will be issued containing the results from a digital computer code based on the reduced van der Waals equation.

7702-4750

Figure 7. Geometry of the Bubble at the Heat Transfer Surface

TABLE 5
SUPERHEAT RANGE FOR INCIPIENT BOILING

Approximate Liquid Velocity (ft/sec)	Wall Superheat	
	Minimum (° F)	Maximum (° F)
3	26	169
4	11	144
5	2	67
6	6	45
7	4	24
8	8	29
9	1	47

those predicted by the reduced van der Waals equation, but also below the trend indicated by the dynamic model,⁽⁴⁾ and the bubble sizes coincident with the cavity diameter spectrum observed by electron microscope.

The dynamic model predicts the trend of wall superheat in the low Reynolds number range for turbulent flow but, with increasing velocity, and consequently increasing Reynolds numbers, the thickness of the laminar sublayer decreases and the effect of the irregularities in the heat transfer surface becomes more pronounced. Turbulence invades the laminar sublayer and another source of energy is available to supply the minimum work required to create the vapor phase. This occurs right at the heat transfer surface where the contact angle may reduce considerably the required minimum work, as shown by the parametric curves for f_o and f_c in Reference 1.

The connection between the turbulent process and incipient superheat is possible if the energy possessed by the turbulent eddies contributes to the formation of incipient bubbles.

It is well-known that for fully developed turbulent flow (i. e., large Reynolds numbers, Re) there is a universal pattern in which the transfer of a constant power density exists, i. e., the kinetic energy from the larger eddies is transferred to the smaller eddies until it is finally dissipated by the eddies with the

smallest size. The Kolmogorov energy spectrum, in the limit, for very large Reynolds numbers is:⁽⁵⁾

$$\mathcal{E}(k) = Ak^{-5/3} \epsilon^{2/3} \quad \dots (5)$$

where the kinetic energy contained by eddies per unit mass is $\mathcal{E} = \int \mathcal{E}(k) dk$, k being the wave number and ϵ is the mean power dissipation per unit mass, which, in the cascading energy process, corresponds to the power (kinetic energy rate) transferred from larger to smaller eddies. A is a dimensionless constant. On dimensional considerations:

$$\epsilon \sim \frac{(\Delta u)^3}{\ell},$$

where ℓ is for the order of the size of the largest eddies (external scale) and it is also the characteristic length, while Δu is of the order of magnitude of the variation of the mean turbulent velocity over the distance ℓ .

In a given case, the energy spectrum exhibits the simplified form indicated in Figure 8, according to Expression 5. The source of energy at wave numbers k_ℓ in correspondence to the length ℓ , and the sink of energy (dissipating eddies) at the wave numbers k_0 , of the size ℓ_0 (internal scale) and below, are shown in Figure 8.

Effecting the integral for $\mathcal{E}$ and neglecting the contribution from the term coming from the smallest eddies, since $\ell \gg \ell_0$,

$$\mathcal{E} \propto \left(\frac{\epsilon}{k_\ell} \right)^{2/3} \quad \dots (6)$$

This formula can be written as

$$\mathcal{E} \propto (\epsilon \ell)^{2/3} \sim (\Delta u)^2 \quad \dots (6')$$

but as Δu is the order of the bulk velocity of the flow u , then the total kinetic energy contained by the eddies per unit mass is simply

7702-4748

Figure 8. Energy Spectrum in the Limit of Very Large Reynolds Number

$$\phi \propto u^2 \quad \dots (6'')$$

We assume that this energy ϕ represents the kinetic energy part of the stream contributing to the energy $W_{\min}$ required for the formation of a noncollapsing vapor bubble. Then it follows from Expressions 3 and 6'' that

$$W_{\min} \propto u^2 \quad \dots (7)$$

In order to facilitate the representation of this latter result it is possible, in a first approximation, to express the factor $p' - p$ in Formula 3 by ΔT , the wall superheat, by using the Clapeyron-Clausius formula.* This leads to

$$\Delta T \propto u^{-1} \quad \dots (8)$$

*This is possible because of the modest superheat detected in the velocity range under consideration.

7702-4749

Figure 9. Wall Superheat vs Velocity

which is the trend shown in Figure 9. In this figure, the upper points, denoting the maximum wall superheat values, correspond to a minimal contribution from the kinetic energy contained by the eddies, while the lower points, denoting the minimum wall superheat values, correspond to a maximal contribution. These points are tabulated in Table 5, and the shadowed area in Figure 9 indicates the range of wall superheats and velocities covered by the present experimental runs. But this trend, as obtained by using the total kinetic energy contained by the eddies, may be misleading because most of the energy is contained in the large size eddies (as shown by the energy spectrum in Figure 8) whose penetration into the laminar sublayer zone is never completed. In consequence, it is worthwhile to examine the contribution for the kinetic energy of the eddies in the smallest size range. If this is so, the energy δ' contributing to $W_{\min}$ would be

$$\delta' \propto \left(\frac{\epsilon}{k_0}\right)^{2/3} \sim (\epsilon \ell_0)^{2/3}.$$

But for the energy dissipating eddies, the Reynolds number for the internal scale is of the order of 1. This leads to

$$\ell_0 \sim \frac{\ell}{Re^{3/4}}$$

where Re , as usual, is the channel Reynolds number. Therefore:

$$\delta' \propto \frac{u^{3/2} \nu^{1/2}}{\ell^{1/2}} \propto u^{3/2}$$

if ℓ and ν are constant. On this basis,

$$W_{\min} \propto u^{3/2}$$

and

$$\Delta T \propto u^{-3/4} \quad \dots (8')$$

which denotes the trend also indicated in Figure 9.

Representative data of Chen,⁽⁶⁾ for incipient boiling of potassium, are plotted in Figure 9 and show their trend to be in agreement with the previous derivations.

This preliminary study must be improved because neither the whole kinetic energy contained per unit mass of the eddies, nor the smallest size eddies (internal scale), precisely determines the trend of decreasing wall superheats with increasing velocities. But there is no question that, by taking these two extreme cases, definite trends are shown indicating the link existing between incipient boiling and the propagation of turbulence into the laminar sublayer with increasing velocities.

D. TRANSFUGUE

The two-phase portion of TRANSFUGUE is being redeveloped, and combined with the liquid phase portion of the code which was completed earlier and reported in AI-AEC-12970.⁽¹⁾ Preliminary calculations indicate that the numerical solution methods render stable results, which are presently being interpreted on physical grounds.

A number of integration schemes were investigated for TRANSFUGUE. The first order explicit predictor (Adams-Bashforth) and implicit corrector (Adams-Moulton) of order 2 proved adequate for preliminary calculations. This integration scheme was used for the time integration of the energy equation and the momentum integral along the boiling channel.

Mass velocities are obtained by recursion using the discretization in space (along the channel) of the mass conservation equation together with the momentum integral. This process is described by Birkhoff and Kimes,⁽⁷⁾ but in this work the equation of state $\rho = \rho(p, h)$ was replaced by an equation of the form $\rho = \rho(p^*, h)$ where p^* was a fixed reference pressure. (Here ρ is the fluid density and h the specific enthalpy of the fluid). But in contrast to this, in TRANSFUGUE the pressure dependence of the fluid properties is kept, and is evaluated iteratively at each time step.

The pressure dependence iteration scheme, which is crucial for the determination of boiling, is presently being evaluated from test problems. It appears, from preliminary calculations, that a fairly fine space-time mesh is

required in the vicinity of channel boiling. It is anticipated that a variable mesh flexibility will be built into the code.

E. REPORTS AND TECHNICAL PAPERS

1. A draft of a comprehensive, 5-year work plan, for "Boiling Studies for Sodium Reactor Safety," (Atomic Energy Commission Task 6G, Nuclear Safety Program) was written and submitted to AEC-RDT.

2. The topical report, "Effects of Velocity, Oxide Level, and Flow Transients on Boiling Initiation in Sodium," by D. Logan, C. J. Baroczy, J. A. Landoni, and H. A. Morewitz, AI-AEC-12939, was issued.

3. A technical paper, "Effects of Velocity, Oxide Level, and Flow Transients on Boiling Initiation in Sodium," by D. Logan, C. J. Baroczy, J. A. Landoni, and H. A. Morewitz, was accepted for presentation at the Winter Annual ASME Meeting. This paper will be published in a symposium volume dealing with liquid metal heat transfer.

IV. EVALUATION OF EFFORT TO DATE

A. TWO PHASE THERMAL HYDRAULICS

The pressure drop-flow characteristics (check curve) of the 3-channel test section were obtained experimentally with boiling sodium. The check curve did not exhibit the predicted flat pressure drop region during the period when each channel successively attained boiling. However, because of channel geometry, heat input, and operating condition differences between the experiment and SODIFAZE prediction, a valid comparison was not possible. Further check curve experiments, in conjunction with code predictions based on actual experimental conditions, are required.

B. THREE-PIN TANTALUM SHEATHED HEATER

The 3-pin tantalum sheathed heater has been demonstrated as an excellent research tool for use in studies involving steady boiling of sodium.

C. BOILING INITIATION THEORY

The initiation of boiling when turbulent flow of superheated liquid sodium prevails in a heated channel is characterized by two distinctive trends for the wall superheat versus velocity.*

The early determinations of superheat in the low Reynolds number range (i. e., when the vertical projections due to the heat transfer surface roughness are negligible in comparison to the laminar sublayer thickness) indicated an increasing trend for maximum superheat pressure with increasing velocity. But as the liquid flow becomes more turbulent the thickness of the laminar sublayer decreases and turbulence in the laminar sublayer is more prevalent.

Theoretical investigation of sodium superheat for Reynolds numbers well into the turbulent flow regime indicates that an additional energy source for nucleating the incipient boiling is available. A preliminary effort contained in this report shows that the decreasing trends for the incipient wall superheat are in correspondence with the kinetic energy possessed by the eddies produced by the turbulent flow.

D. TRANSFUGUE

Many difficulties which have prevented a numerically stable solution to the partial differential equations in TRANSFUGUE have been eliminated. This is significant in that it will allow a more careful evaluation of computer results in terms of the physics models which have been incorporated into the code. It is possible that examination of results in terms of the fineness of the space-time mesh will also test the stability of the method. It appears that this will be possible in the near future.

V. NEXT REPORT PERIOD ACTIVITIES

Additional 3-pin tantalum sheathed heaters will be fabricated and two-phase thermal hydraulic testing will be continued using these heaters. Emphasis will be on examining the effect of heater power misbalance on the shape of the "check" curve and its comparison to the SODIFAZE code predictions.

---

*This dimensional interpretation can be expressed in dimensionless form as already shown in Figure 39, p. 85, of AI-AEC-12767.(8)

REFERENCES

1. "Annual Technical Progress Report, LMFBR Safety Programs, GFY 1970," AI-AEC-12970, August 15, 1970
2. L. D. Landau and E. M. Lifshitz, Statistical Physics (Pergamon Press Ltd., 1958), p. 478
3. D. Logan, C. J. Baroczy, J. A. Landoni, and H. A. Morewitz, "Effects of Velocity, Oxide Level, and Flow Transients on Boiling Initiation in Sodium," AI-AEC-12939, September 1970
4. D. Logan, C. J. Baroczy, J. A. Landoni, and H. A. Morewitz, "Effects of Velocity, Oxide Level, and Flow Transients on Boiling Initiation in Sodium," paper accepted for publication at the Winter Meeting of the ASME, New York, November 1970
5. G. H. A. Cole, Fluid Dynamics (Methuen and Co. Ltd., London, 1962) p. 201
6. J. C. Chen, "Effect of Turbulent Flow on Incipient Boiling Superheat," Technical Working Group on Liquid Metal Thermal Science, Brookhaven National Laboratory, May 22-23, 1969
7. G. Birkhoff and T. F. Kimes, "CHIC Programs for Thermal Transients," WAPD-TM-245, February 1962
8. D. Logan, C. J. Baroczy, J. A. Landoni, and H. A. Morewitz, "Studies of Boiling Initiation for Sodium Flowing in a Heated Channel," AI-AEC-12767, September 30, 1969