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QUARTERLY TECHNICAL PROGRESS REPORT
LMFBR SAFETY PROGRAMS
OCTOBER-DECEMBER 1971

AEC Research and Development Report

Atomics International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304

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The preceding Progress Report was AI-AEC-13014

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Program: Reactor Development

AEC Task: 10 - Nuclear Safety, Characterization of Sodium Fires and Fission Products

Project Manager: H. A. Morewitz

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I. PROJECT OBJECTIVES

The general objective of this project is to develop experimentally verified analytical models for postulated LMFBR accidents involving release and transport of energy and aerosols (sodium, PuO_2 , and fission products) in support of: (1) FFTF safety development needs, and (2) LMFBR Demonstration Plant Safety analysis, engineered safeguards design, and siting. Postulated LMFBR accidents under consideration by this project include sodium pool and spray fires, core disassembly accidents, and fuel accidents. Information derived from this project is essential to the realistic assessment of FFTF-LMFBR accident consequences, required for placing meaningful limits upon the design pressure and leak rates of containment barrier, as well as the site boundary. The objectives of this project correspond to those of Tasks 10-2.6 and 2.7 of the "LMFBR Program Plan, Section 10, Safety," (WASH-1110).

II. MAJOR ACCOMPLISHMENTS FY 1972

An initial series of water jet impingement tests was completed to obtain information on the characteristics of jet breakup and droplet formation required for the development of models of sodium jet discharge hydrodynamics for hypothetical LMFBR pipe-rupture accident analysis.

Two sodium jet discharge simulation tests were completed in the Large Test Vessel (LTV) with a 1-in. sodium jet impinging on a horizontal plate in an inert atmosphere ($\text{O}_2 < 0.015\%$). Data were obtained for pressure rise history, sodium drop size distribution, and distribution of drop rainout within the vessel.

Improvements in the development of a cell pressurization model for sodium jet discharge have proceeded to point where simultaneous droplet heat transfer and oxidation can be calculated so that the influence of cell oxygen concentration on pressure rise can be evaluated. Recent experimental information and the model were used for a revised state-of-the-art assessment of the FFTF heat transfer system (HTS) cell pressure rise following the hypothetical pipe-rupture accident.

Empirical relations between the number of aggregates in an agglomerated particle and its "shape factor" correction for settling and further agglomeration have been found.⁽¹⁾ These relations can be programmed into the HAA-3 aerosol agglomeration code and will eliminate the use of a reduced agglomerate settling velocity independent of its size.

III. PROGRESS DURING REPORT PERIOD

A. SIMULATIONS OF SODIUM JET DISCHARGE

1. Sodium Jet Tests in LTV

The sodium jet discharge studies provide experimental information required to confirm theoretical models which are being developed to characterize the consequences resulting from hypothetical pipe-rupture accidents in FFTF or other LMFBF primary heat transfer system cells. The data obtained during these sodium jet tests will be compared with water jet tests so that scaling of parameters, i. e., temperature and pressure rise, effective volume of droplet formation, and overall heat transfer coefficients, can be directly applied with confidence to any system with verified accident models.

The hypothetical pipe-rupture accident postulated during operation of the FFTF is assumed to result from a guillotine rupture of the vertical riser on the primary sodium pump exhaust. Under these conditions a jet will have an exit velocity which will reach 36 ft/sec and be issued from pipes about 16 in. in diameter. The resulting jet will strike the ceiling of the enclosure depending on its distance from the rupture point. The droplet diameter and distribution determines the maximum pressure rise.

The scheduled sodium jet tests are for characterization of drop formation and disperse geometries resulting from vertical impingement of a sodium jet onto a horizontal plate. The geometries and conditions considered for this test series include pipe diameter, discharge distance, sodium release velocities, and operating sodium temperatures. Characterization of gas temperature-pressure consequences, resulting spray pattern, and droplet size and distribution are to be made. These data will then be compared with previously conducted water jet test results for scoping and initial modeling verification. The first test series must be limited to low masses of sodium, low injection velocities and to 1-in. pipes. Figure 1 shows the sodium injection system and other pertinent measurement stations.

The first two tests in this series (Na Jet Tests, No. 3 and No. 4) consisted of the following initial conditions: Na temperature = 990°F, oxygen content = <0.015%, gas temperature = 68°F, dewpoint = 37°F. The sodium was ejected from a nozzle located 4.5 in. below a horizontal plate at the top of the vessel. The plate was 4 ft x 4 ft stainless steel, 5 mil thick, backed with transite. Observations were made of the gas temperature at various positions, the plate temperature, the fallout pattern, and the droplet size distributions. The jet velocity and drive pressure were also monitored. A recording balance was used to measure the fallout rate and dewars filled with liquid nitrogen were used to obtain the droplet sizes as well as the radial spray fallout patterns by mass. Most of the data was recorded on magnetic tape. Some attempt was made to measure the temperature of the droplets as they hit the floor by attaching thermocouples to thin sheets of stainless steel.

The most important observations of these tests were the pressure rise, the particle size distribution, and the fallout pattern. Other observations are still being made.

Figure 2 shows the sodium jet velocity for the two tests. It can be seen that all of the sodium was released within about 3.2 and 5.8 sec. The spike at the end of the velocity time trace for Test No. 3 is due to the sodium gas interface traveling past the electromagnetic flowmeter. The product of the velocity and pipe area can be integrated to obtain total volume of sodium released after

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Figure 1. Sodium Jet Injection System

Figure 2. Sodium Jet Velocity vs Time for Tests 3 and 4

any time. Figure 3 shows this integration. The gas temperature data at several locations were not representative of the average corresponding to the pressure rise history shown in Figure 4. The peak pressure of about 0.78 psig for Test 3 is equivalent to a 28°F temperature rise, but the individual thermocouples had temperature rises up to 100°F. Additional thermocouples were mounted for Test 4 and temperature rises were observed which varied from 7 to 156°F. This is somewhat consistent with the model which assumes that the droplets heat up only a fraction of the total gas. The vessel time constant obtained from the pressure decay curve is about 276 sec, ($T_{50} = 190$ sec) indicating that the peak pressure which occurred in about 5 sec is the adiabatic pressure rise. The jet velocity for Test 3 was sufficient to cause some fraction of the ejected sodium to hit the vessel walls (10 ft diam) even though similar tests with water indicated that none of the liquid reached the vessel walls. This is consistent with the approximate model developed in Section III-A-2-b, which shows that sodium will travel significantly further along the plate before experiencing the same reduction in velocity as the water jet. This model was used to estimate the jet velocity for Test 4 that would prevent wall impingement.

Figures 5 and 6 show the area integrated mass distribution of the fallout, as well as the size distribution of the droplets collected at the positions shown. Size distributions were not made at each collection point. As mentioned, the higher velocity of Test 3 caused the sodium to splash against the walls and this accounts for the shift in the peak fraction from near the wall (4 to 5 ft) for Test 3 to near the center of the tank (1 to 2 ft) for Test 4. No sodium was found on the wall-mounted collection cups during Test 4.

The total distribution of all the collected drops regardless of position, for both tests is shown in Figures 7 and 8. Figure 7 gives the frequency distribution while Figure 8 shows the cumulative distribution plotted on log-probability paper.

The time sequence of events in Test 4 was as follows: the initial acceleration toward the plate, obtained from differentiation of the velocity-time curve, was 20 ft-sec^{-2} , followed by a 1.25-sec delay before the thermocouple on the top plate showed a temperature increase. The distance between the EM flow-meter and the top plate was about 6 ft which is consistent with the measured

Figure 3. Sodium Released vs Time for Tests 3 and 4

Figure 4. Pressure Rise History for Tests 3 and 4

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Figure 5. Distribution of Fallout with Selected Size Distribution, Jet Test No. 3

Figure 6. Distribution of Fallout with Selected Size Distribution, Jet Test No. 4

Figure 7. Total Sodium Drop Size Distribution for Tests 3 and 4

Figure 8. Cumulative Mass Distribution of Fallout Material at Stated Velocities

acceleration value. After a time period of 1.25 sec, about 2 lb of sodium had passed the EM flowmeter and about 1 lb had struck the plate raising its temperature to $\sim 800^\circ\text{F}$, which is also consistent with the heat capacities of the steel and sodium. The time difference between the rise in temperature of the top plate and a collector plate on the floor of the vessel (a fallout distance of 25 ft) was about 1.4 sec which is also consistent with large droplets falling with little or no drag.

2. Models of Sodium Jet Hydrodynamics

Attention has been directed primarily to the case of a liquid jet impinging vertically on a horizontal ceiling, where it tends to break up into two portions, one of which splashes back while the other forms a sheet on the ceiling that runs out for some distance from the point of impact and then falls off. The characteristics of impinging liquid jet behavior which are of most interest to pipe-rupture accident analysis are the drop size after jet breakup and the dispersion or rain-out geometry of the drops.

a. Drop Size

Experiments with water jets have indicated that the sizes of the droplets ultimately formed by the splashback and falloff processes are insensitive to the jet velocity, and possibly diameter; therefore, an attempt was made to determine drop sizes from a dimensionless parameter depending only on the properties of the liquid. Such a parameter is

$$N = \rho \sigma d / \nu^2$$

where

ρ = density of liquid

σ = surface tension

ν = viscosity

d = drop diameter.

Using for water the values

$$\sigma/\rho = 73 \text{ cm}^3 \text{ sec}^{-2}$$

$$\nu/\rho = 0.01 \text{ cm}^2 \text{ sec}^{-1},$$

and the experimental size estimate

$$d = (0.27 \pm 0.165) \text{ in.},$$

the value $\bar{N}$ of N calculated for the mean value $\bar{d}$ of d is

$$\bar{N} = 0.50 \times 10^6.$$

This being very far from unity, the idea that N controls the drop size appears doubtful. Further doubts are raised when the drop size for sodium that gives the same value of N is calculated, using the values for sodium

$$\sigma/\rho = 183 \text{ cm}^3 \text{ sec}^{-2}$$

$$\nu/\rho = 0.00285 \text{ cm}^2 \text{ sec}^{-1}.$$

The result is

$$\bar{d} = 0.0087 \text{ in.},$$

which is improbably small.

In fact, subsequent tests with sodium (Na Jet Tests 3 and 4) resulted in drop sizes considerably larger than this, and sometimes even larger than the water drops, thus confirming the failure of the attempted scaling law. Moreover, the insensitivity of drop size to defining conditions in water jets does not appear to extend to sodium jets.

It seems likely that the drop size is sensitive to surface properties other than surface tension, which have a strong influence on the surface oscillations of the drops. The energy that breaks up the liquid into drops is at first in the form of energy of surface oscillations, and the drops stop breaking into smaller ones when the damping of the oscillations dissipates the energy before the drops break. It is probable that there is a viscous resistance to surface growth that greatly increases the damping of the surface oscillations. Qualitative information on such effects is provided by the effect of oil in smoothing waves on water, the rise of bubbles in water, and the attenuation of underwater sound by air bubbles, but the quantitative information (even for water, and far more for sodium) is too intricate and too little developed for useful application to the drop-size problem.

b. Laminar Sheet Behavior

The liquid sheet that commonly forms on the ceiling appears more tractable analytically than the liquid that splashes from the ceiling. Estimates of the Reynolds number in the sheet indicate that it may sometimes be in laminar flow, and the significance of viscosity is also indicated by experiments showing that the free sheet formed by the impact of a jet on a small plate is often considerably larger than the constrained sheet formed by the impact of the same jet on a large plate or ceiling. A laminar sheet is somewhat like a laminar boundary layer, for which simple theories exist that can serve as models in treating the sheet. These considerations have motivated the development of the following theory of steady flow in a laminar sheet.

Cylindrical coordinates are used with radii r measured from the center of the impinging jet, and with the axial coordinate z measured from the ceiling into the liquid. The effects of gravity and surface tension are ignored, only viscosity and inertia being retained. The axial component of velocity is neglected, and the radial component $U(r, z)$ is assumed to have a velocity profile of the form

$$U = \alpha(r) \cdot \left[z/\delta - \frac{1}{n}(z/\delta)^n \right], \quad \dots(1)$$

where δ = thickness of the sheet.

This velocity profile is mainly linear, but modified by an n^{th} power term chosen so as to satisfy the free-surface boundary condition.

$$\partial U / \partial z = 0 \text{ at } z = \delta. \quad \dots(2)$$

The value $n = 2$ would require a pressure gradient in the Navier-Stokes equation for radial flow, and is accordingly forbidden, but all values of $n \geq 3$ are to be considered.

$$\bar{U}(r) = \frac{1}{\delta} \int_0^\delta dz U(r, z) = \left(\frac{1}{2} - \frac{1}{n+n^2} \right) \alpha(r) \quad \dots(3)$$

and the total radial flow, for which the constant value W must be determined by the flow in the jet, is

$$W = 2\pi r \rho \delta \bar{U}(r) \quad \dots(4)$$

Solution of Equations 1 through 4 in conjunction with momentum change considerations results in the following velocity profile relationship.

$$\frac{1}{\bar{U}} - \frac{1}{\bar{U}_0} = \beta_n \frac{\nu \rho}{W^2} (r^3 - r_0^3) \quad \dots(5)$$

where

$$\bar{U} = \bar{U}_0 \text{ at } r = r_0$$

$$\beta_n = \frac{(2\pi)^2}{3} \frac{\alpha U}{M/\bar{U}W}$$

M = momentum transfer rate through cylindrical surface of height $\delta(r)$ and radius r ,

and

$$M/\bar{U}W = \frac{1}{3}(\alpha/\bar{U})^2 \left[1 - \frac{6}{n(n+2)} + \frac{3}{n^2(2n+1)} \right].$$

The numerical values of $\alpha/\bar{U}$ from Equation 3, of $M/\bar{U}W$, and of β_n are found to be fairly insensitive to n for $3 < n < \infty$. This is the reason that a theory simplified by the use of a prescribed velocity profile is acceptable.

This theory is both consistent and practical only if there is a radius r_0 at which the mean velocity $\bar{U}$ has not decreased much from the mean velocity $\bar{U}_0$ of the impinging jet, but beyond which the basic assumption of laminar flow throughout the thickness of the sheet is valid. In fact, however, there must be a range of r in which the laminar boundary layer fills a significant fraction, but not all, of the thickness of the sheet, and the mean velocity $\bar{U}$ probably decreases significantly in that range. Conclusions based on Equation 5 are therefore largely tentative. Exceptions are:

- 1) Equation 5 has the correct limit behavior at large r , since this behavior does not depend on the constants of integration.

- 2) An increasing jet diameter will increase the sheet thickness at fixed r , thereby increasing the Reynolds number. The transition to laminar flow being determined by the Reynolds number is thus shifted to larger radii.

The relation of the sheet to the jet is completed by noting that the flow rate in the jet of diameter D is

$$W = \frac{\pi}{4} \rho D^2 \bar{U}_0 . \quad \dots(6)$$

Introducing this relation, the Reynolds number of the jet,

$$Re = \rho D \bar{U}_0 / \nu \quad \dots(7)$$

and the dimensionless ratio,

$$f = r_0 / D \quad \dots(8)$$

into Equation 5, and solving for $\bar{U}/\bar{U}_0$, the result is

$$\frac{\bar{U}}{\bar{U}_0} = \frac{1}{1 + \left(\frac{4}{\pi}\right)^2 \frac{\beta_n}{Re} [(r/D)^3 - f^3]} . \quad \dots(9)$$

This relation is shown in Figure 9 for the case $n = 3$, for which

$$(4/\pi)^2 \beta_3 = 41.2 .$$

As the mean velocity $\bar{U}$ decreases with increasing r , according to Equation 9, the thickness δ of the sheet must vary to maintain the flow rate W . Equations 4 and 6 yield

$$\frac{\delta}{D} = \frac{1}{8} \frac{D}{r} \frac{\bar{U}_0}{\bar{U}} . \quad \dots(10)$$

This relation, with $\bar{U}/\bar{U}_0$ taken from Equation 9, is shown in Figure 10, which shows that the thickness decreases at first because the sheet is spreading, but

ultimately increases to compensate for the reduction in velocity by the viscous drag.

Preliminary evaluation of the results in Figures 9 and 10 suggest that large-diameter jets impinging on an overhead ceiling may exhibit different impact behavior than small-diameter jets. The impact behavior of small-diameter jets may be controlled by viscous shear and surface tension, while gravity and surface tension may primarily control large-jet impact behavior.

c. Sheet in Potential (Irrotational) Flow

The theory of the laminar sheet is inconclusive, not only because of the difficulty with the boundary condition already noticed, but also because the omission of gravity suppresses the possibility that the sheet falls off the ceiling at some sufficiently large radius. An improved theory would include gravity, and also divide the sheet into a laminar boundary layer next to the ceiling and a potential-flow region filling the rest of the sheet. The first step toward this improvement is to solve the problem of the sheet in potential flow, the introduction of the boundary layer being reserved for a later stage of the development.

Theoretical studies were initiated for potential flow of the sheet for steady and unsteady flow. Results thus far suggest that a physical instability may exist under steady sheet flow which corresponds to the sheet falling off the ceiling. Investigation of this point will require the formulation of the flow in the free sheet that forms when the constrained sheet falls off the ceiling.

d. Application of Numerical Methods

Because of the limitations of analytical solutions, which are only available by approximate methods, it has seemed worthwhile to attempt to use numerical methods. Accordingly, a deck of the code ZUNI, which implements the SMAC method of numerical hydrodynamics, has been acquired from Los Alamos, and is being assimilated. The code includes gravity and viscosity, but not surface tension, though methods for doing so have been developed at Los Alamos. A possible difficulty is that solutions may be unstable for low-viscosity fluids such as water or sodium, but this is not known to be serious without an investigation, and some useful results may be attainable anyway.

Figure 9. Liquid Jet Impingement on a Flat Plate - Velocity Decay

Figure 10. Liquid Jet Impingement on a Flat Plate - Liquid Sheet Thickness

B. DEVELOPMENT OF VAULT PRESSURIZATION MODEL FOR SODIUM JET DISCHARGE

A sodium spray droplet energy transfer model which includes sensible heat and chemical energy transfer, is being developed as part of the more complete analysis which will determine the resulting containment vessel temperature and pressure effects. The approach is to start with a single droplet model which will provide for droplet internal energy balances and surface temperatures so that appropriate burning correlations for conditions approaching sodium saturation temperatures as discussed previously may be used.

Finite difference formulations in the model describe the internal energy distribution of a single droplet with time. Loss of mass from the droplet surface as well as changes in physical properties are accounted for in each time step. This first phase of the model has been completed and surface heat transfer correlations with vaporization and combustion effects are being incorporated. As the droplet approaches the sodium saturation temperature, the model will account for changes in the burning rate as discussed below. In each time step, appropriate physical properties will be adjusted for changes in the droplet velocity while falling through the containment vessel. This model will be expanded to include multiple droplet sizes and gas recirculation in the containment space.

The model will be checked against results obtained experimentally in sodium spray tests.

A single droplet vaporization burning model was presented in the GFY 1971 annual technical progress report.⁽²⁾ This model resulted in an equation for the burning of droplets at or near their saturation temperature. The burning rate is expressed as:

$$\frac{dm}{dt} = \frac{-\pi \rho_\ell D k}{8} (2 + 0.6 \text{Pr}^{1/3} \text{Re}^{1/2}) \quad \dots(11)$$

where

$$k = \frac{8\lambda_g}{\rho_\ell C_{p_g}} \ln(1 + B) \quad \dots(12)$$

and

$$B = \frac{\Delta H_c Y_o}{\Delta H_v r} + C_{p_g} \frac{(T_f - T_1)}{\Delta H_v}, \quad \dots (13)$$

m = droplet mass

ΔH_c = heat of combustion

ΔH_v = heat of vaporization (ΔH also includes the heat required to heat the particle to the vaporization temperature)

Y_o = mass fraction of oxidant at infinite distance from the particle surface

r = stoichiometric mixture ratio, $r = \frac{\text{Weight of } O_2^*}{\text{Weight of Na}}$

T_f = gas temperature at infinity*

T_1 = vaporization temperature

λ_g = mean coefficient of thermal conductivity of gas in combustion zone

C_{p_g} = mean specific heat of gas in combustion zone

ρ_l = density of the droplet.

In an LMFBFR pipe rupture accident, the initial sodium temperature is 1100°F or less, well below the lowest sodium saturation temperature of 1660°F; therefore, initially the sodium vaporization will be small and the burning rate will be essentially controlled by the diffusion of oxygen to the surface. In fact for low oxygen concentrations and large droplets, one of the areas of primary interest, the droplet temperature may not reach saturation before falling to the floor.

As an estimate of the burning rate under these circumstances we can use the relations for the burning of solid fuels. According to Spaulding⁽³⁾ the transfer number (B) under these circumstances degenerates to:

$$B = \frac{Y_o}{r} \quad \dots (14)$$

*In Reference 2 these terms were incorrectly defined.

and

$$k = \frac{8\lambda_g}{\rho_l C_{p_g}} \ln \left(1 + \frac{Y_o}{r} \right) \quad \dots(15)$$

which for low oxygen concentration ($O_2 \leq 2\%$) we can write:

$$k = \frac{8\lambda_g Y_o}{\rho_l C_{p_g} r} \quad \dots(16)$$

From Equations 13 and 14, we can see that the loss of significant surface evaporation will reduce the transfer number by a factor of $2[(\Delta H_c / \Delta H_v) \approx 2]$ at most when the gas temperature (T_f) $\leq 1660^\circ\text{F}$. For the condition in FBR flow oxygen environment ($O_2 < 5\%$) accidents, the burning rate can be expected to be reduced by only a factor of 1.5 or less when the droplet temperature is significantly below its saturation temperature.

Equations 11 and 16 were solved parametrically using the following nominal values for the fixed terms:

$$\lambda_g = 0.0308 \text{ Btu/hr-}^\circ\text{F-ft}$$

$$C_p = 0.255 \text{ Btu/lb-}^\circ\text{F}$$

$$\text{Pr} = 0.661$$

$$\nu = 70 \times 10^{-5} \text{ ft}^2/\text{sec (kinematic viscosity)}$$

$$\rho_l = 51 \text{ lb/ft}^3$$

$$r = 1/2.88$$

The results presented in Figure 11, can be used to estimate the burning rate for oxygen concentrations up to 2% O_2 , when the droplet surface temperature is well below the saturation value. In a detailed evaluation, the change in the fluid properties with time should be accounted for, along with the possible buildup of sodium oxide on the droplet surface.

Figure 11. Burning Rates for Sodium Drops in Low Oxygen Concentration ($O_2 \leq 2\%$)

C. LARGE SCALE SODIUM POOL BURNING TESTS

1. Two-Cell Test Planning

Detailed test planning was initiated for two-cell sodium pool burning tests in the large test vessel (LTV). These tests will provide experimental data for verification of various portions of the SOFIRE II two-cell computer code. This code is currently employed in LMFBR/FFTF safety analysis to predict the pressurization of the outer containment building following a major sodium spill in a primary coolant system cell which is open to the building during maintenance.

The geometry of the LTV will be changed to the two-cell configuration. The configuration will consist of the "cell" and "secondary" volumes, separated by a floor which is positioned between the bottom section and the mid-section of the vessel. The "cell" volume occupies approximately 700 ft³ and the "secondary" 1400 ft³. The area of the opening through which gas interchange is maintained can be adjusted from 1 to 12 ft² and the thickness of the opening will be varied between 1 in. and 1 ft. A 10-ft² heated pan will be used to provide natural convection. Sodium will also be introduced to the system through a vessel wall penetration from a preheat and transfer tank during later tests. The preheat and transfer tank is capable of handling sodium charges up to 300 lb at temperatures of 1000°F. Instrumentation which provides experimental data for consequence assessment and modeling verification will include measurements of temperature, pressure, oxygen concentration, humidity, aerosol plating, and fallout and a net gas flow across the opening between the two volumes. Most of the initial flow patterns will be obtained with heated pans and nonradioactive tracer gases in order to avoid the complication contributed by the oxide particulates. The atmosphere will be normal air. Test conditions required for these test series will be based upon simulated LMFBR and FFTF shutdown and/or operating conditions.

D. AEROSOL BEHAVIOR STUDIES

1. UO₂ Vaporization Generator Tests in LTC

A successful test was completed in the Laboratory Test Chamber (LTC) for an improved UO₂ arc-vaporization aerosol generator system which will be used

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Figure 12. Typical Time Sequence of Aerosol Generation and Release Following CDA

in the LTV tests on UO_2 -aerosol behavior. Several major improvements have been incorporated into the present system:

- 1) The iron electrode was replaced with tungsten. This electrode forms the initial arc to heat the UO_2 up to a point where it can conduct. The melting point of the tungsten is higher than the iron and thus it remains available longer to strike an arc when the UO_2 is vaporized away.
- 2) A reduced oxygen environment is used, which better simulates the Core Disassembly Accident (CDA) environment and does not oxidize and burn up the tungsten electrodes.
- 3) The steel crucible which holds the UO_2 powder was conically shaped so that the molten UO_2 could not slump away from the center electrodes.
- 4) Pressed UO_2 pellets at 90% of the theoretical density allow more UO_2 to be loaded into a crucible. This increases the amount of UO_2 aerosol which can be suspended in a given time.

Results of this test show that rapid vaporization of UO_2 can be achieved by using current values in excess of 200 amp.

E. REALISTIC AEROSOL SOURCE FROM THE DBA

In order to establish in a realistic way the environmental impact of the leakage of suspended fuel material from the reactor containment subsequent to a severe core disassembly accident (CDA), a realistic characterization of the basic aerosol source which is produced in the disrupted core must be made. Additionally, a credible mechanism must be established for the transport of this basic aerosol from the core to the containment regions. A preliminary effort has been made to resolve these two fundamental aspects of the overall aerosol release problem. Using these results as a basis the changing character of the total aerosol can be studied in terms of its suspended concentration as a function of time and location. A typical time sequence of the aerosol generation and release process following a CDA is shown in Figure 12.

The initial fuel aerosol density is based on the quantity of fuel vapor in the core after core disassembly and the quantity of molten fuel assumed to participate in the fuel-coolant interaction. The fuel vapor is assumed to condense initially to an aerosol particle size of approximately $0.1 \mu\text{m}$ by mass, based on AI experience with UO_2 vapor sources in a relatively cold environment. The portion of the core which is molten is assumed to produce, via the fuel-coolant interaction, a particle size distribution with a mass median diameter of approximately $150 \mu\text{m}$ based on current experimental data.⁽³⁾ The solid portion of the core is not expected to contribute significantly to the aerosol source. This initial aerosol particle size distribution can be expected to exist at the beginning of the sodium vapor expansion phase of the accident. The total aerosol composition is conserved within the expanding vapor region up to the point of escape from the reactor vessel, although model refinement could realistically permit aerosol removal during this phase.

The aerosol and sodium vapor expansion bubble tend to remain in the core region until the dynamic response of the reactor vessel and top shield plug is terminated. In this near quiescent state, the vapor bubble with its associated aerosol may rise to the top of the reactor vessel due to buoyancy forces. Then the vapor plus aerosol may escape from the vessel through potential openings in the machinery dome or shield plugs depending on the design. The process up to this release phase requires a time period on the order of 0.5 sec.

In a typical FBR, the fuel aerosol in the early phase of the core disassembly accident may have a bimodal particle size distribution due to the two distinct sources of aerosol particles (fuel vapor and molten fuel). This distribution will change its character during the first one-half second of its existence due to the agglomeration phenomena which can occur to a significant degree in the relatively dense environment. In fact, all of the vapor may condense on to the larger molten particles as the temperature of the vapor bubble decreases. By starting with a realistic source distribution and calculating its changing character during this early time, a realistic aerosol source for the containment can be obtained. For example, see Table 1.

Let the mass M_R released into a primary volume V have an initial particle radius of 0.1 micron by mass. If the leak rate is constant and 10%/day and the

TABLE 1
MASS LEAKED FOR VARIOUS INITIAL SIZES
AND CONCENTRATIONS*

Diameter of Initial Median Size (microns)	Initial Mass Suspended in Inner Containment		Mass Leaked to Outer Containment, M_L (gm)	Mass Fraction Leaked, f_L
	M_R (gm)	Concentration (gm/cm ³)		
0.2	1000 kg	235	75	7.5×10^{-5}
0.2	100 kg	23	86	8.6×10^{-4}
0.2	10 kg	2.3	103	1.03×10^{-2}
0.2	1 kg	0.23	130	0.130
1.0	1 kg	0.23	270	0.270
† { 10 50 100 100 50	1 kg	0.23	8	0.008
	1 kg	0.23	0.4	4×10^{-4}
	1 kg	0.23	0.08	8×10^{-5}
	10 kg	2.3	0.80	8×10^{-5}
	10 kg	2.3	4.0	4×10^{-4}

NOTES:

*Leak rate from inner to outer containment is 10%/day. Particle density is 1 gm/cc. Fraction of M_R which is Pu is arbitrary.

†No agglomeration assumed.

concentration is high, then agglomeration and the resultant fallout will control the leaked mass M_L into the reactor building. On the other hand, if the particles are large and of low concentration, so that little agglomeration occurs, then the fallout and leak rate control the leaked mass M_L . Thus large releases consisting of large particles contribute little to the dose at the site boundary. A more realistic appraisal of the source may result in the elimination of a large fraction of dose present attributable to plutonium.

G. FFTF SAFETY DESIGN APPLICATION

1. HTS Cell Pressure Rise

A preliminary assessment was conducted previously to determine the magnitude of the pressure rise in an FFTF Heat Transfer System (HTS) cell following

a hypothetical guillotine pipe-rupture accident. Recent experimental information on sodium droplet diameters following jet breakup has been used in conjunction with appropriate geometry considerations in the computer code NALTV to determine resulting vault pressure rise in the main FFTF heat transfer cell following a pipe-rupture accident in the vertical section of pipe from the pump to the IHX. The analysis assumed that both an upward and downward sodium jet resulted from rupture.

The computer code NALTV is a transient thermal model which incorporates the combustion formulations of Spaulding.⁽³⁾ A nodal description of the sodium-vault gas environment within a prescribed control volume is used to determine the thermal energy transfer from the sodium to the gas. All energy from combustion is assumed to go to the sodium mass initially with subsequent heat exchange to the gas. It is assumed that the sodium spray droplets contact the gas in the rainout zone only and do not mix with gas outside this zone. The expansion of the control volume gas is assumed to be adiabatic and the resulting increase in cell pressure is determined accordingly.

The analysis has been performed parametrically allowing the droplet diameter to range from 0.05 to 0.20 in. Recent experimental results indicate that diameters of approximately 0.20 in. are more likely. Based upon Bechtel drawings (SK-10602-14) showing the pump, IHX, and cell structure, the spray volume was assumed to be limited to 43.5% of the entire cell gas volume. This assumes that gas above the elevation of the pump ceiling is excluded from the rainout volume. A total of 18,800 lb of sodium, initially at 1050°F, would be injected into the cell, which initially has a gas temperature of 100°F, following the hypothetical pipe rupture.

The pressure rise rate in the cell with varying droplet diameter is given in Figure 13. The smaller diameter permits greater combustion and heat transfer to the gas and therefore the sharper rise in pressure for the $D = 0.05$ in. curve is as expected. In the case of the 0.05-in. droplet, the available oxygen is consumed in approximately 1.25 sec after sodium is introduced, whereas for the 0.20-in. droplet, oxygen is not totally consumed for nearly 3 sec. The analysis here was performed at the 2% oxygen concentration for the cell. For the 0.20-in.-diam droplets, the resulting cell pressure rise is approximately 10 psig.

Figure 13. FFTF HTS Cell Pressure History as a Function of Droplet Diameter

The effect of varying oxygen concentration initially in the vault is shown in Figure 14. For the 2% curve, a slight peaking occurs in the pressure due to the rapid consumption of all oxygen present in the spray volume by the large quantity of sodium mass. In the nominal 1% oxygen case, all available oxygen has been consumed in less than 1 sec and there is no further energy generation and pressure peaking does not occur. For such a low O_2 environment with the assumed conditions, a cell pressurization of approximately 10 psig is predicted. This pressure value is within the short-term design pressure of 12 psi for the FFTF HTS cell.

Figure 15 has been included to demonstrate the dependence of pressure upon rainout volume fraction. The larger the rainout volume fraction, the greater is the interaction between sodium and the volume of gas, thereby increasing cell pressure. The NALTV model does not account for any recirculation of the gas, which would have an effect similar to increasing the rainout volume fraction.

Figure 14. FFTF HTS Cell Pressure for Various Initial Cell O_2 Concentration

Figure 15. FFTF HTS Cell Pressure History as a Function of Rainout Volume Fraction

IV. EVALUATION OF EFFORT TO DATE

The acquisition of experimental data from the sodium jet impingement tests in the LTV in an inert atmosphere, in conjunction with the progress on the development of a cell pressurization model, has significantly improved our present capability for realistic evaluation of HTS cell pressurization parameters. The results of the two sodium jet tests in terms of hydrodynamics of jet breakup still require resolution in terms of scaling, with respect to comparison with the previous water jet tests. An important observation from the sodium tests, however, is that the mass median size of the sodium droplet formed after impingement is still relatively large (e.g., 0.2-in. diam by comparison with previous assumptions in accident analyses. All of the above information has permitted an improved assessment of the FFTF HTS cell pressure rise following a pipe rupture accident. Although the results of the current evaluation indicate a higher pressure rise than the previous study, bases for the present calculations have a considerably stronger foundation and the values are still in the acceptable range for design. For the FFTF HTS cell and other LMFBR's, a relatively large mass of sodium is discharged and dispersed compared to the mass of gas in the system and thus in all cases, the drop size and rainout geometry control the resultant pressure rise. If the drops are less than 0.05 in. in diameter, all of the sensible heat will be lost during their transport through the gas. The oxygen content of the cell makes a more significant contribution to the total pressure as the released sodium mass and temperature are reduced. The effect of oxygen on total pressure increases rapidly as the O_2 concentration exceeds 2%. Therefore a low oxygen cell atmosphere is recommended if the postulated accident can produce pressures near that for which the system is designed.

The development of a hydrodynamics model for predicting the behavior of sodium jet breakup after impingement on a horizontal surface, over a wide range of initial conditions, is currently one of the more difficult of all of the activities in the cell pressurization area. Theoretical studies thus far have now been made in sufficient detail to obtain a reasonable definition of the problem and evaluation of the utility of the limited information available in the literature. Several promising approaches to the solution of the hydrodynamics model have

emerged from these studies and now can be pursued in the next several months. One such approach is the ZUNI code derived from the SMAC methodology for solving these types of problems. The applicability and adaptation of the code to sodium jet breakup is uncertain, but worthy of investigation.

The recent improvements to the UO_2 arc-vaporization aerosol generator indicate that a satisfactory solution to the problem of generating reasonably high UO_2 concentrations in the Large Test Vessel may now be available. Some additional testing in the Laboratory Test Chamber, to optimize operating conditions of the generator, will enable determination of the practical limits of the system.

V. NEXT REPORT PERIOD ACTIVITIES

Additional sodium jet tests will be conducted in the LTV at various oxygen concentrations and with larger quantities of sodium.

Development of the sodium drop heat transfer and oxidation portions of the cell pressurization model will continue. Comparisons of model with sodium jet test results will be made and evaluated.

Modeling of the hydrodynamics of jet impingement and breakup will be studied using the ZUNI code to evaluate the applicability of numerical methods solution.

Additional testing of the improved UO_2 arc-vaporization aerosol generation technique will be completed and UO_2 aerosol tests will be performed in the LTV.

Detailed planning for two-cell natural convection and sodium pool burning tests in LTV will be completed and natural convection mass transfer tests will be initiated with a heat source other than liquid sodium.

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