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**ANNUAL TECHNICAL PROGRESS REPORT
REACTOR SAFETY
GOVERNMENT FISCAL YEAR 1978**

DOE Research and Development Report

*Prepared for the United States
Department of Energy,
Division of Reactor Research and Technology,
under Contract Number EY-76-C-03-0824*

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Rockwell International

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Program:	LMFBR Safety		
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I. PROJECT OBJECTIVES

- 1) Perform LMFBR risk assessments in LOA-3 and LOA-4 areas to develop key accident scenarios and methods of quantifying the risks thereof. Identify inherent and engineered safety features and detail work necessary to qualify applicable safety features as effective in risk reduction.
- 2) Within existent capabilities, perform tests and analysis necessary to qualify the safety features as effective. At present, this work is assessing the following attenuation mechanisms:
 - a) Plugging of leaks by aerosols in the process of escaping through containment barriers (LOA-3)
 - b) Coagglomeration of sodium and fuel aerosols to produce larger particles that quickly fall out (LOA-4)
 - c) Interaction of molten core debris with underlying materials that tend to dilute and retard melt-through as well as minimize amount of gas produced (LOA-3)
 - d) Fallout of sodium aerosols released to the atmosphere (LOA-4).

II. MAJOR ACCOMPLISHMENTS DURING FISCAL YEAR 1978

A preliminary risk assessment of an LMFBR has been performed.⁽¹⁾ Certain accident scenarios have been identified as key to the process of risk reduction.

These are: (1) high energy release CDA with containment failure due to energetics, (2) a moderate energy release CDA with containment failure due to energetics, and (3) a low energy release CDA with containment failure due to core debris behavior.

The most probable of the accidents is the latter, because of the lower energy release involved, and the most significant risk reduction can be achieved by working in this area. This is usually identified as Line of Assurance -3 (LOA-3) in which risk reduction is achieved by preventing breach of containment. Risk reduction can be achieved by substantiation of either in-vessel or ex-vessel core retention mechanisms. The in-vessel mechanisms require some sort of nonpassive cooling and are generally regarded as less credible than ex-vessel retention methods. Therefore, it is believed that most effort at AI and ESG should be concentrated on ex-vessel retention methods. It may be that ordinary concrete with a steel liner will provide adequate core retention, and first efforts in melting and pouring UO_2 have been directed along this line.

In the past year, it has been demonstrated that both carbon steel and stainless steel can withstand direct contact with molten UO_2 without melt-through.⁽²⁾ As UO_2 is poured on a plate, it spreads out into a thin layer, which rapidly cools and forms a solid crust next to the plate. This insulating layer retards the temperature rise in the plate. Heat transfer calculations generally confirm this result, except that temperature rise is even less than calculated, possibly due to poor thermal contact between UO_2 and substrates.

As a result of an accident, core debris mixed with sodium and/or sodium oxides would escape to the environment. LOA-4 is associated with the amelioration of the effects of this most improbable accident through natural processes which lead to dispersal and fallout close to the source. Experimental studies⁽³⁾ involving the release of Na to the atmosphere have been conducted at the Idaho National Engineering Laboratory. These tests conducted in cooperation with the National Oceanic and Atmospheric Administration (NOAA) have provided a measure of the fallout to be expected following a sodium spray or pool fire.

The sodium oxide aerosols were shown to agglomerate very quickly and mostly fall out within a few hundred meters of the source. Since, in an HCDA the sodium oxides would coagglomerate with any released fission products and mixed

oxide fuel, a similar rapid fallout for the mixture can be postulated. The agglomeration that occurs either in a mixed oxide-sodium or mixed oxide-sodium oxide environment is a strong function of the concentration. Higher concentrations result in larger agglomerates, which tend to fall out close to the source.

Thus, even a very severe accident, which produced much airborne debris, would not necessarily have worse consequences than a less severe accident. The higher concentration aerosols agglomerate into larger particles, which fall out more quickly. This has been demonstrated by a series of tests [High Concentration-Temperature Tests⁽⁴⁾] in which very high concentration aerosols were produced in a sodium-oxygen blowtorch. The particles produced fell out in a matter of seconds.

Further tests [Multiple-Bend Leak Tests^(2,4)] have shown that aerosols do not flow through small leaks very readily but rather tend to plug the leaks. Even the aerosols that do pass through are enlarged in size. These tests were performed with sodium oxide and UO_2 aerosols separately.

In summary, a preliminary risk assessment for the LMFBR has been performed. This assessment indicates that the most significant risk reduction could be accomplished in the LOA-3 area by tests that demonstrate adequate ex-vessel core debris retention. Preliminary tests have been made that demonstrate the transient behavior of molten UO_2 , which tends to spread out and cool rather than melt through a steel plate, at least initially.

Further tests have indicated that even if fuel-sodium oxides are released to the environment, they will mostly fall out near the source of the leak. Also, leaks are quickly plugged by the aerosols flowing through, and those aerosols that do pass through are enlarged in size.

A. SUBTASK D — HIGH-TEMPERATURE-CONCENTRATION AEROSOLS

1. Introduction

Certain types of hypothetical reactor accidents in LMFBR's could produce large amounts of aerosolized fuel debris mixed with sodium vapor and fission gas. The accompanying sodium slug motion would stretch the head tiedown bolts, allowing the aerosol mixture that reached the cover gas to escape into the reactor

containment building. The radiological hazard associated with such airborne debris is reduced due to the increase in size of the agglomerated particles. Large particles cannot easily escape through leaks, and those that do fall out rapidly. Attempts are being made to assess the proportion of aerosol particles escaping through broken or displaced head seals and the size of particles that do escape.

Previously, plugging of leak paths has been demonstrated for both sodium oxide and uranium oxide. During this report period, preliminary tests were carried out to measure the size and concentration of coagglomerated uranium oxide and sodium vapor as produced in the tank of the arc-melter. The intensely hot arc vaporizes copious amounts of uranium oxide, which then condenses in the argon furnace atmosphere to form particulates of UO_2 . Simultaneously with turning off the furnace current, liquid sodium is sprayed into the crucible where it is vaporized almost instantaneously. The sodium then condenses out on the UO_2 particulates to form coagglomerated $UO_2 + Na$ particulates. These fall out within the furnace.

A turntable was constructed to determine fallout as a function of time. The collector is a horizontal wheel that slowly turns at a known rate. The wheel carries 12 glass slides that are exposed to the furnace atmosphere, one by one, at 3-s intervals. The mass collected is measured by weighing the slides before and after exposure.

The data collected is presently being analyzed. Indications are that coagglomerated aerosols of $UO_2 + Na$ fall out more rapidly than UO_2 alone, but further testing is necessary.

B. SUBTASK F — LARGE-SCALE MOLTEN FUEL TESTS

These tests involve arc-melting and pouring of UO_2 onto reactor structural materials to simulate the aftermath of an LMFBR CDA. Results of tests have been previously reported.⁽²⁾ To extend these tests, it is planned to install an auxiliary induction heater to maintain the UO_2 at high temperature after pouring. This will simulate the effect of fission product heating.

A 100-kW inductive generator has been acquired for this purpose. The generator is being installed adjacent to the arc-melting tank. After a pour, a

pancake-shaped inductive coil will be rotated downward so as to be directly above the molten UO_2 . The generator will then be turned on. It is expected that the high-frequency currents induced in the UO_2 will maintain it in molten condition for an extended time period.

C. SUBTASK M — SODIUM RELEASE TESTS

1. Introduction

Five sodium release tests have been conducted in the atmosphere at the Idaho National Engineering Laboratory. These tests were conducted jointly with the Air Resources Laboratory (ARL), National Oceanic and Atmospheric Administration (NOAA).

In four of the tests, hot liquid sodium was sprayed out from an elevated tank. The other test involved burning in an open pan. The resulting airborne sodium oxide particles were characterized as a function of downwind distance from the release point. Sampling stations were placed on a grid to measure particle fallout, concentration, size, chemical species, and tracer gas concentration.

The purpose of the tests was to simulate a hypothetical break in an LMFBR heat transport system, which resulted in sodium being released to the atmosphere. The tests showed that most of the sodium oxide particles rapidly agglomerate near the source and quickly fall out. The remaining particles drift downwind where they gradually convert to sodium carbonate. If the sodium is nonradioactive, there is little hazard except in the immediate region of the release.

2. Test Description

A description of the test and results is given in Reference 3. Releases were made from a 30-m high tower located at the apex of a test grid. A plan view of this grid (Grid III Research Facility) is given in Figure 1. Eight concentric arcs were located 25, 50, 100, 200, 400, 800, 1600, and 3200 m from the tower. Each arc was provided with remotely controlled sampling stations as shown in the figure. During the tests, the wind was from the southwest, and thus stations in the northeast sector were used. Table 1 gives the test conditions for the five tests. Several types of data were collected. These are discussed in the following paragraphs.

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Figure 1. Grid III Research Facility

TABLE 1

RELEASED AIRBORNE PARTICLE TEST CONDITIONS

Test No.	Test Date	Quantity of Sodium Released (kg)	Release Period (min)	Release Height (m)	Type of Release	Wind Direction ($^{\circ}$ true)	Wind Speed (m/s)	Ambient Temperature ($^{\circ}$ C)	Dew-point ($^{\circ}$ C)	Stability Category*
1	5-23-78	22.1	3.92	5	Spray	224	3.98 [†]	17.0	2.69	D
2	6-7-78	25.1	5.25	6	Spray	249	4.20 [†]	25.9	-0.11	A
3	6-13-78	75.0	3.28	30	Jet	218	5.95 [§]	24.3	1.14	A
4	6-16-78	55.3	60.8	0	Pool	222	8.0 [†]	13.9	-3.36	A
5	6-21-78	75.0	3.65	30	Jet	235	5.30 [†]	25.9	-0.59	A

*Stability categories are designed by NRC $\Delta T/\Delta Z$ criteria

[†]Measured at 6 m elevation

[§]Measured at 30 m elevation

a. Meteorological Data

This includes wind velocity and temperature as measured at different heights on the apex tower. During the tests, SF_6 tracer gas was released. This was collected at the various sampling positions to determine plume dispersion. This data will be published.

b. Fallout Data

Fallout collection trays were placed at various positions to determine the amount of fallout as a function of distance from the release point. The amount of fallout is given in Figures 2 through 6 and also in Table 2. The fallout, presumed to be sodium oxide Na_2O , was determined by flame photometry.

c. Particle Sizes

Particle sizes were determined by direct measurement of photomicrographs and by impactors. Glass slides (22-mm diameter) were placed on all of the collection stations and fallout particles were sized by direct measurement. The impactors yielded some data also, but in general, the plume did not touch the collection sites. A summary of the size data is given in Table 3.

d. Particle Concentration

Particle concentration was determined near ground level by drawing air samples through a filter and then analyzing for sodium by means of flame photometry. Because the plume was generally well above ground level, the measured concentration was very low. The data is given in Table 4.

e. Combustion Product Species

Filter samples were analyzed for various chemical species: Na_2O , Na_2O_2 , NaOH , and Na_2CO_3 . Because the amount of material collected was very small, the analysis must be considered tentative. Most of the material collected was Na_2O . A typical analysis (Test 5 at the 100-m station) showed 90% Na_2O , 0% Na_2O_2 , 1% NaOH , and 9% Na_2CO_3 .

3. Analysis of Results

a. Comparison with Calculation

The COMRADEX IV Code was modified in order to calculate fallout. Comparisons of the slopes of deposition versus downwind distance were made with

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Figure 2. Particle Fallout vs Downwind Distance — Test 1

Figure 3. Particle Fallout vs Downwind Distance - Test 2

Figure 4. Particle Fallout vs Downwind Distance - Test 3

Figure 5. Particle Fallout vs Downwind Distance — Test 4

Figure 6. Particle Fallout vs Downwind Distance — Test 5

TABLE 2
MAXIMUM FALLOUT DEPOSITION FROM RELEASE TESTS 1 THROUGH 5

Distance (m)	Fallout Deposition (g/m ²)				
	Test 1 (Pasquill D)	Test 2 (Pasquill A)	Test 3 (Pasquill A)	Test 4 (Pasquill A)	Test 5 (Pasquill A)
1				1 E+3	
2.7	51				
3.0		7.4			
6.1		1.0 E-1			
7.7	11.5				
9.1		3.9 E-1			
12.2	8.0	4.0 E-1			
15.2		5.2 E-1			
15.7	5.4				
18.2		2.0 E-1			
18.9					
21.3		3.9 E-1			
21.5	3.8				
25	6.1 E-1	5.7 E-1	6.1	1.1	3.8 E-1
35					4.0
50	8.7 E-1	2.4 E-1	2.8 E-2	6.4 E-1	7.2 E-2
100	3.7 E-2	1.7 E-2	1.2 E-2	6.2 E-2	6.0 E-3
200	3.4 E-2	1.7 E-2	1.5 E-3	2.5 E-2	2.3 E-3
400	3.6 E-3	1.5 E-3	6.4 E-4	3.4 E-3	9.1 E-4
800	1.7 E-3	3.1 E-3	7.4 E-4	9.5 E-4	6.5 E-4

TABLE 3
SIZE OF AIRBORNE PARTICLES

Distance (m)	Particle Size (μm)						
	Photograph (Size Range)				Impactor (AED ₅₀)		
	Test 2	Test 3	Test 4	Test 5	Test 3	Test 4	Test 5
25	220-620	340-475	32-72	40-140	5.2	1.1-5.6	—
50	220-620	—	20-138	—	—	1.4-6.4	—
100	220-620	14-38	22-100	28-30	—	1.1	—
200	—	52	26-42	62	—	—	—
400	—	46	96	92	5.5	—	—
800	—	86	30	32	—	—	—

TABLE 4
PARTICLE CONCENTRATIONS AT 1-m ELEVATION

Distance (m)	Particle Concentration (g/m^3)				
	Test 1 (Pasquill D)	Test 2 (Pasquill A)	Test 3 (Pasquill A)	Test 4 (Pasquill A)	Test 5 (Pasquill A)
25	—	9.4 E-3	8.2 E-2	4.3 E-3	2.8 E-4
50	—	4.0 E-3	2.8 E-3	6.2 E-4	7.7 E-2
100	8.5 E-3	5.2 E-3	9.3 E-3	1.0 E-3	1.4 E-3
200	3.4 E-3	2.9 E-3	2.2 E-3	9.0 E-4	4.3 E-3
400	3.4 E-3	3.2 E-3	1.3 E-3	—	2.7 E-3
800	4.0 E-3	3.0 E-3	2.8 E-4	1.9 E-3	3.4 E-4

experimental results. While the slopes of curves showed reasonable agreement, the absolute magnitude of predicted fallout was in considerable variance with that observed. This discrepancy is probably due to errors in calculating terminal velocity of falling particles. This is presently being corrected.

b. Rate of Deposition

A sodium fire produces a dense aerosol cloud. The majority of the particles tend to agglomerate as soon as formed into quite large particles, which immediately fall out. The particles escaping agglomeration remain airborne for some time until they eventually fall out or agglomerate with a dust or water particle. If the sodium burns in open air with a wind blowing, the larger particles will be deposited near the source while the smaller drift downwind. Generally, the larger particles account for a major fraction of the mass of the cloud, but the visible cloud is mostly due to a residue of very small particles ($<5 \mu\text{m}$), which scatter the light effectively. Thus as a cloud is drifting downwind, it is depositing large particulates and losing most of its mass even though it remains opaque. The large particulates being lost are too few in number to be readily visible while they are falling out under the visible cloud.

The relative amount of fallout depends on the original rate of agglomeration. A high concentration would result in more agglomeration and thus more fallout. This is a fortunate situation because it tends to limit the consequence of a sodium fire.

c. SUBTASK N — RISK ANALYSIS

1. LOA-3 Program Plan

The objective of this subtask is to identify those LOA-3 activities that would lead to a substantial reduction in LMFBR risk and are cost effective to pursue. Then a program plan will be made that will lead to the resolution of key LOA-3 issues in a cost effective manner.

A preliminary program plan⁽¹⁾ has been drafted. A final plan is to be completed midway into FY 1979 with results to be presented in the form of an Approval-in-Principle Report. This will be a 5-year program plan that describes

in detail the activities to be performed (i.e., purpose, description, cost, schedule) and is intended to establish a firm basis for the continuation of the AI activities.

The following is a synopsis of the work performed in developing the preliminary program plan.

a. Detailed Risk Assessment

Probabilistic assessments were performed of scenarios associated with CDA's in order to identify those accident paths having the greatest risk. The AI commercial LMFBR design provided a basis for this work. The risk assessment was performed using event trees associated with LOA-3 as the basic framework. The result was a ranking of high potential R&D activities to which the PAHR safety activities could be directed so as to reduce the risks.

b. Scale-Effect Assessments

In order to determine a minimum experimental size (i.e., molten fuel sample size) required to depict PAHR phenomena in a prototypical manner, one-dimensional and two-dimensional heat transfer calculations have been performed for a typical PAHR experimental simulation (e.g., molten fuel settling on the reactor cavity concrete floor following reactor vessel melt-through). Because sodium effects were not included in these scoping calculations, these experimental simulations attempted to describe the behavior of the fuel and concrete prior to the subsequent involvement of sodium, which follows the molten fuel through the failed reactor vessel. The time frame of interest is therefore fairly short (i.e., for the CRBR an estimated 120 s is required for sodium to reach the cavity floor). While the thickness of the molten fuel debris that rests on the cavity floor is a function of the amount of core debris involved, the degree of bed levelling, and the reactor cavity configuration, a typical thickness of interest would be about 5 cm. For instance, for the CRBR, a 4.8-cm debris bed thickness results when the core plus upper and lower blankets are spread uniformly across the cavity floor (12.2 m). An equivalent value for the AI pool design (24.4-m diameter cavity) is approximately 2.5 cm. As uncertainties associated with the amount of fuel-spreading phenomena can increase these heights by a factor of 2 or 3, a choice of a 5-cm bed for these scoping calculations was deemed sufficient.

The large size of a typical LMFBR reactor cavity floor implies that the attack of the fuel melt on the concrete can be expected to closely approximate a one-dimensional problem. Consequently, a one-dimensional heat transfer calculation was performed to provide a reference behavioral model for the expected LMFBR scenario. A 5-cm thick molten UO_2 pool (initial temperature of 3000°C with 3% decay heat) was assumed to be resting on a 0.3-m thick concrete slab initially at 100°C (no fuel-concrete mixing was allowed). Figure 7 displays the key one-dimensional model results. The parameter of most interest is the melt progression into the concrete during the 120-s time frame of interest, since that is the behavior that ultimately will have to be simulated accurately during the experiment. Figure 8 shows this melt progression for the 3% decay simulation presented in Figure 7, along with a limiting case of 0% decay heat. For the limited time frame of interest, i.e., time before sodium becomes involved, decay heat is seen not to be a significant factor.

In order to estimate the ability of the experimental simulations to match these one-dimensional results, a two-dimensional heat transfer model was developed. Three two-dimensional cases were examined: 5-kg, 15-kg, and 30-kg molten UO_2 samples were each spread out in a 5-cm thick layer in concrete crucibles having diameters of 11.3, 19.6, and 27.7 cm. The initial conditions were identical to those used in the one-dimensional analysis. For this study, it was estimated that an acceptable simulation would be achieved if about 70 to 80% of the surface area behaves like the simulation shown in Figures 7 and 8. The results are shown in Figures 9, 10, and 11. The concrete melt profiles clearly indicate that the 5-kg experiment would not demonstrate the desired one-dimensional behavior, since less than 5% of the surface area has acceptable melting behavior at 120 s. The 15- and 30-kg analytical experiment simulations indicate that after 120 s, about 40 and 65% of the surface, respectively, behaves like the one-dimensional simulation during the first 120 s.

Recognizing that during the earlier times the area of good simulation is larger, and that analytical models used did not account for potential fuel and concrete mixing, 30 kg appears to be an acceptable lower limit for melt size.

Additional two-dimensional heat transfer calculations have been performed to assess the impact of: (1) thicker fuel melt sizes, (2) cooling coils on the

Figure 7. Temperature Distributions Following a Transient (1-Dimensional)

Figure 8. Melt Progression into Concrete (1-Dimensional)

Figure 9. Melt Progression into Concrete (2-Dimensional; 11.3-cm Diameter Crucible)

Figure 10. Melt Progression into Concrete (2-Dimensional; 19.6-cm Diameter Crucible)

Figure 11. Melt Progression into Concrete (2-Dimensional;
27.7-cm Diameter Crucible)

crucible walls, and (3) minimum conductivity insulation placed along the insides of the crucible wall. Only in the latter case was the desired one-dimensional behavior achieved with fuel melt sizes less than 30 kg. However, questions regarding the integrity of such insulation in the presence of molten fuel and its potential for introducing nontypical behavior have indicated that such PAHR experiments would not be advisable.

In summary, these preliminary scoping analyses have indicated that prototypic PAHR experiments of the type considered feasible require fuel sample sizes at least as large as 30 kg. Further heat transfer analyses are planned to confirm this tentative conclusion. In addition, assessments will be made of other PAHR phenomena that may be affected by melt size such as convective cooling within the melt, gas sparging effects, and retention bed inhomogeneities. In any event, the size capability of the AI arc furnace pouring facility (15 to 100 kg of molten UO_2) would seem to be sufficient to conduct prototypic PAHR experiments.

2. LOA-4 Program Plan

a. Introduction

In GFY 1978, SOMIX-1 was used to investigate the sodium spray burning phase of LMFBR core disruptive accidents (CDA's) in order to provide a basis for LOA-4 risk analysis. Head failure can result from high-velocity impact by the sodium pool followed by rotating plug jump, loss of rotating plug seals, control rod ejection, failure of instrument tubes or breach of in-vessel transfer machine ports. A typical large LMFBR head structure showing the various rotating plugs, plug seals, hold-down keys, rotating gear housings, and access ports is shown in Figure 12. Head failure can lead to significant sodium injection into the containment building by the residual gas bubble pressure, which forces the upper plenum sodium through the interstitial spaces (e.g., rotating plug gaps, control rod housings) in the breached head structure.

b. Hydraulic Analysis

An evaluation of large-scale containment building spray fires was carried out for two assumed CDA energy releases and for the residual bubble pressure shown in Figure 13. In case 1, using the CRBRP gas bubble pressure decay

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Figure 12. LMFBR Head Structure

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Figure 13. Bubble Pressure Following a CDA vs Time

assumption, an initial residual bubble pressure of 20 atm was assumed to be followed by a linear bubble pressure decay to about 2 atm in 10 s. Roughly, this corresponds to a 1700 MJ energy release in a 1000-MWe loop reactor. For the second case, an initial residual bubble pressure of 5 atm was assumed, corresponding to about 800 MJ energy release in a 1000-MWe pool reactor. The head failure modes analyzed included rotating plug jump, loss of head seals (with and without dislocation of the rotating drive housing), and sodium flow through the control rod housings.

Rotating plug positions at various times after pool impact are shown in Figure 14 for the 1700 MJ CDA with an initial gas bubble pressure of 20 atm. The analysis assumed that the pool impact destroyed the head hold-down capability but contributed negligibly to the head velocity; therefore, subsequent motion was determined solely by the residual gas bubble pressure.

The head clears the deck structure in about 2 s, at which time the head velocity is about 2.4 m/s. At this time, the sodium discharge appears to be predominately in a radial direction. At 3.5 s, the plug has a velocity of about 3.7 m/s and is about 4 m above the deck structure (as shown on Figure 14). The sodium and the gas bubble would already have blown out of the head cavity by this time. The plug will rise a few more meters at the most and then fall back to the deck. The general implication from this scenario is that, although massive amounts of sodium can be injected into the containment building during a residual gas pressure plug jump, the injection will be primarily in a radial direction, and the major consequence could be a low-intensity pool fire rather than a high-intensity sodium spray fire.

Sodium discharge through the gaps between the rotating plugs is shown in Figure 15. Calculations were made for discharge with and without the rotating bearing housings (see Figure 12 for details on the bearing housing structure). The assumption here is that the initial impact of the sodium on the head could cause the housing hold-down bolts to fail and dislocate the housing in such a manner that sodium can be injected into the containment building directly through the rotating plug gaps.

Discharge velocities and theoretical (drag-free) injection heights were calculated for both 20- and 5-atm initial bubble pressures using a linear pressure decay as shown in Figure 13. Since the ceiling of the containment building is about 46 m above the rotating plug deck, it is apparent that if the bearing

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Figure 14. Plug Position at Various Times After Pool Impact

Figure 15. Sodium Discharge Velocity With and Without Bearing Housing

housing fails, a 20-atm initial residual bubble pressure has the potential of injecting high-velocity sodium streams through the rotating plug gaps. These could potentially impact on the containment building ceiling. Lower bubble pressures and/or intact bearing housings confine the sodium spray to the lower half of the containment building.

Sodium discharge through control rod housings is illustrated in Figure 16. Because of the large diameter of the housing, the discharge velocities and the injection heights can be quite high, even for the 5-atm residual bubble pressure condition. This analysis was based on the assumption that the control rod drive housings were sheared off just below the reactor cover and the control rods and mechanisms were ejected, providing a direct and unobstructed sodium flow path to the containment building.

To establish a frame of reference for sodium spray injection into the containment building, note that a typical containment building may have the following parameters:

1) Gas volume	= 70,000 - 90,000 m ³
2) Air in building	= 70,000 kg
3) O ₂ in building	= 16,000 kg
4) Na for Na ₂ O	= 70 m ³
5) Theoretical pressure rise	= 5.8 atm
6) Building design capability	= 0.8 atm
7) Sodium directly under rotating plugs	= 700 m ³

It follows that about ten times as much sodium can be injected into the building as is required to react all the oxygen. If all the oxygen were reacted and none of the energy were lost to the surroundings, the theoretical building pressure rise would be about 6 atm. A typical large LMFBR containment building might have a design pressure of about 0.8 atm but could probably withstand an actual pressure rise of about 1.6 atm.

Figure 17 shows the volume of sodium that can be discharged through all the gaps between the rotating plugs. Curves are shown for sodium discharge both with and without the bearing housing. The amount of sodium that is required for

Figure 16. Sodium Discharge Velocity from Control Rod Housing

Figure 17. Effect of Bearing Housing on Sodium Discharge

complete combustion is shown at the bottom of the figure. It is apparent that the gaps have a potential for generating large sodium sprays that could produce significant sodium spray fires in the containment building.

Figure 18 shows the sodium discharge through the control rod housing. A significant number of multiple control rod failures will be required in order to attain the theoretical combustion limit in which all the available oxygen is consumed. However, because of the low hydraulic resistance of the control rod housings, the jet velocities are high, and the sprays may be widely dispersed by impact on the ceiling or internal equipment.

c. Spray Fire Analysis

The SOMIX sodium spray fire analysis code was used to evaluate energy releases for a number of sodium injection rates, corresponding to the various head failure scenarios described above. In order to maximize the oxidation reaction between sodium and the building atmosphere, it was assumed that the spray originated at the ceiling and fell uniformly over the entire containment building cross section to the floor. Physically, this would correspond to a high-velocity sodium jet issuing from the control rod housings or the rotating plug gaps (without the drive mechanism housing) striking the ceiling at high velocity, and breaking up into a spray of drops, which fall uniformly throughout the containment building atmosphere.

The results of spray fire analysis for a number of injection conditions are summarized in Figure 19. The 93-m^3 injection corresponds, roughly, to sodium release from $\sim 10\%$ of the gap area in the rotating plugs. The 21-m^3 and 7-m^3 injections correspond to 3 and 1 control rod failures, respectively.

The calculated maximum pressure rise is about 2.1 atm, as compared to the theoretical maximum of 5.9 atm. The 21-m^3 injection gave virtually the same pressure rise as the larger 93-m^3 of sodium injection. The 93-m^3 injection reacted 84% of the available oxygen as compared to 27% for the 21-m^3 injection. Thus, even though three times as much combustion heat was liberated, the building pressure was not significantly higher for the high-injection case. Since the burning time was too short (~ 12 s) for a significant amount of heat to be lost

Figure 18. Sodium Flow from Control Rod Housings

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Figure 19. Containment Building Pressure Rise

to the walls of the containment building, the pressure effect must be associated with internal differences in the burning of the two sprays. The source of the differences is illustrated in Figure 20.

Figure 20 shows the gas temperature distribution in the containment building at the end of the injection period, which occurs about 12 s after start of sodium injection. Also shown on the figure (by the vertical broken line) is the temperature of the sodium drops as they leave the ceiling. The figure shows that after 12 s of burning, the spray fire for the high-sodium injection case is largely confined to the lower portion of the containment building. This occurs because most of the oxygen in the upper part of the building has already been consumed by the sodium drops, which fell through and reacted with the oxygen in the upper atmosphere during the early phase of the spray fire. Furthermore, as sodium drops, at a temperature of $\sim 820^{\circ}\text{K}$, continued to fall through the high-temperature, oxygen-depleted upper atmosphere, the burning gradually diminished, and the drops began to absorb the prior combustion heat. Thus, the temperature of the upper atmosphere decreased and gradually approached the temperature of the incoming drops.

The gas temperature distribution is reversed for the low-sodium injection case (21 m^3). The drop density is now too low to consume all the oxygen in the upper region. Therefore, strong combustion still exists in the upper atmosphere. It tails off gradually in the lower atmosphere because the mass of the drops has been sharply reduced by burning as the drops passed through the oxygen-rich upper gas layers.

The analysis indicates that containment building pressures may not always increase with increasing sodium injection rates. Beyond a critical injection rate, the oxygen concentration can be reduced to a level where the spray begins to cool rather than heat the gas. It would be extremely difficult for physically realizable sodium sprays to react all of the building oxygen without producing some cooling effect in the oxygen-depleted regions. Thus, the actual pressure rise should always be below the theoretical maximum. By performing more detailed sodium spray fires analysis, it may be possible to establish a reasonable containment design basis pressure for containing the maximum postulated sodium spray fires.

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Figure 20. Comparison of Temperature Distribution Following High and Low Sodium Injection Rates

A high-velocity sodium jet impact on the containment ceiling has generally been assumed to produce a more serious spray fire condition than one in which the spray is confined to the lower region of the containment building. The above analysis indicates that in the case of large sodium sprays, the reverse assumption is more likely to be true. A spray fire in the lower region of the containment building will produce hot combustion gas, which flows up into the upper part of the containment building and forces cold, oxygen-rich gas down into the spray fire zone. Thus, only the cold gas is likely to come into contact with the sodium drops. The hot gas tends to stay well above the spray zone, and most of the combustion heat is available to raise the building pressure.

III. NEXT REPORT PERIOD ACTIVITIES

A. SUBTASK D

Tests of combined UO_2 + Na aerosols will be continued. A special fallout collector will be completed, which will make it possible to preserve an inert atmosphere over collected samples until analysis is completed.

B. SUBTASK F

Installation of the 100-kW induction heater will be completed. Inductive coils will be installed in the furnace tank so that temperature of poured material can be maintained.

C. SUBTASK M

Analysis of sodium release Tests 6 and 7 will be completed, and a test report will be written. Further testing is anticipated, and test plans will be formulated.

D. SUBTASK N

The AI R&D Program will be updated as a consequence of the planning effort. A 5-year program plan for PAHR safety activities will be completed.

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