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SODIUM FIRES ANALYSIS
FOR THE
FAST FLUX TEST FACILITY

HANFORD ENGINEERING DEVELOPMENT LABORATORY
UNITED STATES ATOMIC ENERGY COMMISSION

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FOR THE FAST FLUX TEST FACILITY

J. P. Hale
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ABSTRACT

This analytical and survey report presents summaries of sodium fire cases of practical value for sodium cooled reactor plant safety. Sodium pool fire calculations are reported in depth. Surveys of pool and spray fire calculation methods and experimental progress are summarized where applicable to the present plant design parameters.

For the pool fire calculations various accident conditions are investigated: two-cell configuration in air atmosphere, release of sodium and fission products due to fuel handling, and closed cells with low oxygen atmosphere. Time history curves display the thermal transients to near ambient conditions at the end of 20 to 100 hours. Spray fires are treated for low oxygen conditions.

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INTRODUCTION

The Fast Flux Test Reactor will utilize liquid sodium for the reactor cooling function. Three primary heat transport system (HTS) loops will circulate sodium through the reactor at a maximum bulk outlet temperature of 1050°F.

Since liquid sodium reacts readily with oxygen, water and many other compounds special design provisions have been implemented to ensure that the primary sodium systems will not leak. The reactor primary sodium coolant systems will employ the highest standards of state-of-the-art construction and quality control for circulating sodium in welded stainless steel piping and vessels. This, together with the low sodium pressures employed, leads to the conclusion that any postulated pipe break should be regarded as a hypothetical incident.

Primary sodium systems are all contained in closed inert gas filled cells (1 vol% oxygen) with temperature, pressure, and humidity control. Water systems and combustible materials are excluded from these cells. Pumps, heat exchangers and other components are enclosed with guard tanks to catch leaks from vessels in event they should occur. Leakage of sodium into a 1 vol% oxygen atmosphere precludes flame burning and would produce only minimal reaction heat release in the inerted cell.

During reactor shutdown periods the primary HTS sodium will be maintained in a liquid state with a minimum temperature and pressure of 500 °F and 2 psig or less, respectively. In this situation a primary sodium cell may be open for maintenance with an air atmosphere. Thus, the primary sodium heat transport systems will be maintained at much below their rated pressure and temperature during shutdown so that the probability of leakage will be considerably lower than for at power operation.

The purpose of this document is to demonstrate that even if a pipe leak or even a large scale sodium release should occur that it can be contained successfully without impairing the outer containment vessel capability to limit leakage of airborne radioactivity. The analyses were performed for the purpose of demonstrating the capability of the structure and containment to withstand the temperatures and pressures resulting from sodium fires. Normally operative plant functions which would tend to lessen the consequences of sodium fires were not included; i. e. cooling and ventilating systems. Also as a further conservative measure it was assumed that no operator or system corrective actions took place at the outset or during the sodium fire.

SUMMARY

The findings of this report indicate that the outer containment vessel and the FFTF reactor building structure below grade will withstand the most severe sodium fires accidents postulated. Sodium pool fires accidents can be calculated with accuracies well within the conservatism implied by the initial assumptions for each accident case. Spray fires, while not admitting to exact calculation, have been shown to possess predictable upper theoretical and experimental limits confirmed by several investigators.

Sodium pool fires are highly geometry dependent: cell volume, burning surface area and heat transfer surface areas are involved. The calculations indicated the effect of varying the containment design and accident condition parameters. The following specific cases were investigated: heat transport cell pool fire open to outer containment during plant shutdown, reactor head cavity pool fire open to outer containment, pool fire in closed inert gas filled cell both with and without protective insulation for cell liners; and pool fires in small primary sodium equipment cells.

Results of spray fire theoretical upper limit analysis for small amounts of sodium release indicate no problem for cell pressure retention capability. The hypothetical release of a very large quantity of sodium coincident with a fine particle dispersion could result in overpressure if adiabatic conditions are assumed. A study is now being completed to show that thermal absorption processes will be effective in holding the maximum pressure to tolerable short term peaks in a closed inerted cell.

FIGURE 1 *Sodium Fire Model for HTS Cell Open to Outer Containment Vessel*

- Initial oxygen concentration within containment = 21 vol%
- Outer containment volume = 1,313,000 ft³
- HTS cell free volume = 29,600 ft³
- Steel machinery heat absorbing masses above operating floor = 1 million lb
- Outer containment steel shell thickness, avg = 1-in.
- Outer containment insulation thickness, (on outside of steel) = 2.5-in.
- Overall heat transfer coefficient through steel and insulation = 0.15 Btu/ft²-hr-°F
- Sodium burning surface area (floor area) = 825 ft²
- Vent cross-sectional area, access plugs removed = 101 ft²

Analysis of spill quantities in the range 20,000 to 150,000 lb indicated that a maximum pressure of 2.4 psig occurred in the outer containment for a spill of 35,000 lb. The maximum outer containment steel shell temperature of 241 °F occurred for a sodium spill of 50,000 lb. Time history curves showing gas temperature and pressure and structure temperatures out to 100 hours are shown in Figures 2 and 3 for these two respective cases.

The accident temperature of 241 °F is below the normal design maximum of 250 °F in the steel containment shell, while the accident pressure of 2.4 psig is less by a factor of four than the containment vessel design pressure of 10 psig. In this hypothetical case no atmospheric coolers are assumed to be operating while in actual practice there is no reason to suspect that they would not continue to operate. There-

FIGURE 2 Sodium Pool Fire in HTS Cell Open to Outer Containment
--SOFIRE-II code calculation - 35,000 lb Sodium Spill

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fore the shell temperature is not expected to approach one-half these values except in the hypothetical case.

Calculated temperatures and pressures for other sodium spill quantities are reported in the section on Variation of Parameters.

FIGURE 3 Sodium Pool Fire in HTS Cell Open to Outer Containment
 --SOFIRE-II Code Calculation - 50,000 lb Sodium Spill

2. Reactor Head Cavity

Initial conditions for this pool fire analysis assumed the reactor operating at ultimate sodium outlet temperature capability, 1050 °F. A loss of sodium in the head cavity space has been analyzed for a range of spills from 5,000 to 40,000 lbs at 1050 °F. For the present case a release of 20,000 lb was analyzed. Sodium ejection is restricted to the head cavity space by the top cover plate. At the time of the accident it is assumed that containment valves are closed and there is no leakage or venting into or out of the outer containment vessel, and atmospheric cooling systems are assumed to be inoperative; both are additional conservative assumptions.

The following initial and boundary conditions were used for this analysis (see Figure 4 for model of this case):

- . Initial oxygen concentration within containment = 21 vol%
- . Initial containment air and outside air temperature (at atmospheric pressure) = 80 °F
- . Initial temperature of spilled sodium = 1050 °F
- . Outer containment volume = 1,313,000 ft³
- . Head cavity free volume = 10,200 ft
- . Steel heat absorbing masses above operating floor = 1 million lb
- . Outer containment steel shell thickness, avg. = 1-in.
- . Outer containment insulation thickness (on outside of steel shell) = 2.5-in.
- . Overall heat transfer coefficient through steel containment shell and insulation = 0.15 Btu/ft²-hr-°F
- . Sodium burning surface area = 1050 ft²
- . Vent cross-sectional area in top plate = 300 ft²

Analysis of this accident indicated that pressure rose to a maximum of 4.0 psig at the same time that sodium was consumed. The outer containment shell temperature rose to a maximum of 219 °F. Time history curves showing containment pressure and structure temperatures out to 20 hours are shown in Figure 5. The accident pressure and temperature are well below the design limits of 10 psig and 250 °F for the outer containment vessel. The effects of changes in the sodium spill quantity and vent opening cross-section are discussed in the section relating Variation of Parameters.

FIGURE 4 *Sodium Fire Model for Outer Containment*

FIGURE 5 Sodium Pool Fire in Head Cavity
 SOFIRE-II Code Calculation

3. Fuel Handling Machine Accident in Outer Containment Vessel

Temperature and pressure transients have been calculated for a hypothetical accident in which sodium and fission product decay heat is released directly to the containment vessel air atmosphere. The most conservative assumption was made in regard to sodium combustion: immediate reaction to thermal equilibrium. This hypothetical accident was chosen since the resulting adiabatic pressure, 3.2 psig, is less than one-third the normal design pressure and precludes the more complex, but less severe, case of sodium boiling. At the time of the accident it was assumed that containment valves are closed and there is no leakage or venting into or out of containment and that cooling systems are inoperative; both are additional conservative assumptions.

The following initial and boundary conditions were used in this analysis:

- Initial containment air and outside air temperature (at atmospheric pressure) = 80 °F
- Initial sodium temperature = 1200 °F
- Initial oxygen concentration in containment = 21 vol%
- Outer containment volume = 1,313,000 ft³
- Steel machinery heat absorbing masses above operating floor = 1 million lb
- Outer containment steel shell thickness, avg = 1-in.
- Outer containment insulation thickness, (on outside of steel shell) = 2.5-in.
- Overall heat transfer coefficient through steel shell and insulation = 0.15 Btu/ft²-hr-°F

- . Fission product decay heat, % of core activity one hour after shutdown = 1.7%

The initial sodium reaction raised containment air temperature and pressure to 3.2 psig and 198 °F. From this point the time history curve, Figure 6, shows air temperature and pressure falling rapidly at first as heat is absorbed in the steel masses, rising again due to decay heat absorption, and then slowly diminishing. The calculation was terminated at 100 hours.

4. Heat Transport System (HTS) Cell Closed and Inerted

a. Base Case - Cell Enclosed with 1/4" Steel Gastight Liner

Initial conditions for this pool fire analysis assumed the reactor operating at full power with ultimate sodium outlet temperature capability of 1050 °F. The HTS cell is closed and inerted with nitrogen containing a nominal 1 vol% oxygen during reactor operation. In the hypothetical case of a double-ended sodium pipe rupture in the 16-in. pump outlet, up to 56,000 lb of sodium may be spilled into the cell in one minute. The spill quantity is limited by primary pump coastdown from scram and by pressure buildup in the cell.

It is conservatively assumed that there is no leakage or venting into or out of the cell and that cooling systems are inoperative from the start of the spill.

The following initial and boundary conditions and cell design parameters were used in this analysis (see Figure 7 for cell model):

- . Initial containment gas and structure temperature = 100 °F
- . Initial temperature of spilled sodium = 1050 °F

FIGURE 6 Hypothetical Fuel Handling Accident - Pressure and Temperature Transient

FIGURE 7 *Sodium Fire Model for Inerted Equipment Cell*

- Initial oxygen concentration in cell = 1 vol%
- Quantity of sodium spilled (in 1 minute) = 56,000 lb
- HTS cell free volume = 29,600 ft³
- Heat storing mass in HTS components = 250,000 lb
- Cell steel liner thickness = 0.25-in.
- Cell concrete wall thickness, avg = 5 ft
- Sodium burning surface area (floor area) = 825 ft²

Analysis for this case indicated that cell pressure and temperature reached a maximum of 5.5 psig and 287 °F at 1.3 hours for the maximum sodium spill of 56,000 lb. Time history curves showing gas temperature and pressure and structure temperatures out to 50 hours are shown in Figure 8. A parametric study on sodium spills of 45,000 lb and 65,000 lb is presented in the section on Variation of Parameters.

b. Inerted HTS Cell with Drip Pans and Insulation

The pool fire accident conditions for this case are the same as for (a) Base Case: 56,000 lb of 1050 °F released into the cell in one minute. The cell design parameters are also the same as for the Base Case, the cell completely enveloped by 1/4 in. steel gastight liner. However, in this case the liner is protected by 4 in. of no. 16 firebrick and this, in turn, is covered by a "drip pan," 16 gauge steel sheet. This arrangement forms a pan; Figure 9, covering the cell floor and extending 5 ft above the floor on the walls. The flat surface of the large horizontal shelf 18' x 36' is protected by the same materials.

The time history curve of cell temperature and pressure is shown in Figure 10. Analysis for this case indicated that cell pressure and temperature

FIGURE 8 Sodium Pool Fire in Closed Inerted HTS Cell Primary Sodium Spill Case

FIGURE 9 *Sodium Fire Model for Inerted Equipment Cell with Drip Pans and Insulation*

FIGURE 10 Sodium Pool Fire in Closed Inerted HTS Cell - Primary Sodium Spill Case -
 Drip Pan and Insulation on Cell Floor

reached a maximum of 6.5 psig and 324 °F at 2.5 hours. The calculation was carried out to 50 hours. Analyses for sodium spills of 45,000 lb and 65,000 lb are given in the section on Variation of parameters.

c. Cell Structure Temperatures

The maximum temperatures attained in cell liners and concrete is of importance in determining the effect on reactor building integrity. In Table 1, the maximum temperatures resulting from Base Case (a) are compared with those from Drip Pans and Insulation, Case (b). It can be concluded that the cell floor concrete is adequately protected by the insulating firebrick since maximum temperature at a 1 inch depth did not exceed °F while it rose to 465 °F in the non-insulated case. The insulated 1/4 inch gastight floor liner never exceeded 256 °F while the non-insulated floor liner rose to 895 °F, nearly to the sodium pool temperature.

In either case the concrete beyond a depth of ~6" does not exceed 250°F under accident conditions. One design alternative considers this surface layer to be neglected structurally since there is sufficient reinforced strength in the remaining 4-6 ft. of thickness to maintain integrity. However, if the design choice is made to limit temperatures in the total thickness of concrete to less than 250°F, then the drip pans and insulation configuration may be employed to protect cell liners.

d. Water Release from Concrete

Preliminary estimates of water release from concrete indicate that under the most conservative assumptions ~6 lbs of water could be released from HTS cell concrete surfaces during the high temperature period (~50 hours) following a spill of 56,000 lbs of sodium. The cell temperature distribution is such that the upper half of the cell would be condensing

TABLE 1. Comparison of Steel Liner and Concrete Temperatures for
Sodium Pool Fire in Inerted HTS Cell

Sodium Spill: 56,000 lbs at 1050 °F

	Base Case - No Insulation (Figure 7)	Drip Pans & Insulation Case (Figure 9)
Max. Floor Liner Temperature (°F) (time at max.)	895 9.3 min.	256 20 hrs.
Max. Floor Concrete 1" deep (°F)	465	250
Max. Floor Concrete 3" deep (°F)	330	238
Max. Floor Concrete 8" deep (°F)	208	200
Max. Wall Liner, above sodium pool (°F) (time at max.)	292 1.0 hr	282 4.0 hrs.
Max. Wall Concrete 1" deep (°F)	188	247
Max. Wall Concrete 3" deep (°F)	164	190
Max. Wall Concrete 8" deep (°F)	148	170

moisture while the lower half would be evaporating moisture. The liquid could flow out of the condensing region on an equilibrium refluxing cycle at once every 3 hours. This small rate indicates that a minimal amount of vapor exists in the gas space between liner and concrete at a pressure approximately equal to the cell atmosphere pressure. In this circumstance the cell liner is not in danger of overpressure and the small amount of moisture is contained. More work is proceeding to refine the calculations with the expectation that the total water release can be shown to be less than 1 lb.

5. Reactor Building Small Sodium Equipment Cells

Reactor building small equipment cells containing primary sodium systems were analyzed for hypothetical sodium pool fire accidents. The small cells are closed and inerted with nitrogen containing a nominal 1 vol% oxygen during reactor operation. Sodium spill quantities and temperatures varied, cell design parameters and results are shown in Table 2. It is conservatively assumed that there is no leakage or venting into or out of the cell and that cooling systems are inoperative from the start of the spill.

TABLE 2. Sodium Pool Fires in Small Equipment Cells

Cell Description	Free Volume (ft ³)	Burning Surface (ft ²)	Sodium Spill		Gas Conditions		Basis for Sodium Spill
			Quantity (lb)	Temp (°F)	Press. (psig)	Temp. (°F)	
Closed Loop cell	2,250	120	2,300	1,000	3.0	206	Primary loop inventory
" "	"	"	7,000	1,150	6.2	295	Secondary loop inventory
Closed loop pipeway	12,600	560	2,300	1,000	1.6	163	Primary loop inventory
" "	"	"	7,000	1,150	3.5	232	Secondary loop inventory
Interim decay storage cell	9,300	243	23,000 (NaK)	500	1.3	158	Tank NaK jacket inventory
" "	"	"	8,000 ^a	600	1.6	155	Sodium transfer piping break ^a
Cold trap cell	1,000	100	7,000 ^a	900	3.9	156	Piping break ^a
Sodium storage cell	9,400	594	155,000	500	3.9	257	Storage tank inventory
" "	6,600	"	4,500 ^a	600	1.8	167	Piping break ^a
Sodium over-flow cell	21,700	856	102,000	1,020	7.2	381	Overflow tank inventory
" "	16,900	"	6,000 ^a	1,050	2.6	200	Piping break ^a

^aAssumes leak is detected by leak detection systems and shut off within 15 minutes.

Results indicate that maximum pressures of less than 8 psig were attained during the sodium oxidation and heat dissipation transient, most were in the 2 to 4 psig range. The cell normal design pressure of 10 psig should be adequate.

B. Spray Fires

In the case of a pipe leak the effective jet breakup of sodium into fine particles is highly unlikely with substantial layers of insulation secured to the pipe contributing to a much larger pressure reduction in the sodium stream before it finds its way to the surface. However, as a limiting case in low oxygen environments, a fine particle dispersion (~.02-in. diameter) of high temperature liquid sodium is assumed to be perfectly mixed with the gas in the cell. The heat of reaction and sensible heat in the sodium is transferred directly to the gas atmosphere with little being lost initially to structures and containment walls. Under laboratory conditions, both the Na_2O (monoxide) and the Na_2O_2 (peroxide) reaction products have been observed due to burning in air, however, in 2 vol% oxygen no monoxide was detected.⁽¹⁸⁾ For equal quantities of oxygen consumed the formation of Na_2O_2 evolves ~50% less heat than the formation of the monoxide.

A stoichiometric amount of sodium spray can theoretically consume all of the oxygen present in a low oxygen cell (<5 vol %). This corresponds to a sodium-oxygen molar ratio of 2:1; i.e., 1.1 lb of sodium per 1000 ft³ of gas in 1% oxygen at 100 °F and atmospheric pressure for 100% Na_2O_2 production and 2.2 lb of sodium per 1000 ft³ of gas for 100% Na_2O production. The pressure and temperature in 1 vol % oxygen is 11 psig at 520 °F for perfect thermal equilibrium of reaction product (100% Na_2O_2) and cell gas,

while for 100% Na_2O production a pressure and temperature of 18 psig at 800 °F is calculated. Table 3 provides a comparison of maximum theoretical pressures for reaction to completion.

TABLE 3. Theoretical Maximum Pressures Obtainable in Low Oxygen Volumes Due to Sodium Oxidation to Thermal Equilibrium at Stoichiometric Ratios

Sodium Oxide Product	Stoichiometric Ratio = moles Na/mole O_2	Heat of Reaction (Btu/mole O_2)	Max. Theoretical Pressures (psig)	
			1 vol% oxygen	2 vol% oxygen
Na_2O	4:1	356,400	18	33
Na_2O_2	2:1	219,600	11	20

If unlimited quantities of sodium are available it is at least theoretically possible to heat the gas space to a temperature approaching that of sodium. With this unrealistic assumption and adiabatic conditions the cell pressure would rise to ~25 psig for a sodium temperature of 1050 °F. Analytical work supported by prior experimental studies^(17, 19) is now in progress to determine the practical values of pressure rise under high volume, high dispersal, hypothetical spray conditions.

Currently, calculations have been performed to evaluate the heating effect due to sensible heat transferred from high temperature sodium spray to cell gas. The release of 56,000 lbs in one minute from a hypothetical double ended rupture of a 16 inch pump outlet pipe in the HTS cell was considered for three representative cases: a jet impinging directly on cell vertical wall, jet impinging directly on a cylindrical HTS component, and a jet impinging on the cell ceiling. The third case, impingement on the cell ceiling, gave the most severe transient. At the jet velocities available from $\sim 5,000$ lbs/sec initial discharge rate, no jet breakup was predicted before striking the impinging surface. After striking the ceiling the liquid will spread along the flat surface to a diameter of 7 to 20 ft. before raining down in an annular envelope. This is a cylinder with diameter d and maximum thickness of ~ 2 ft. Perfect mixing was assumed between gas and sodium in this cylinder for ~ 5 seconds before the jet velocity diminished to the limit where it could no longer reach the ceiling. Heat and mass transfer calculations verified that the gas outside the mixing cylinder could not diffuse to and could not be heated effectively by the mass in the cylinder within the 5 second interval that sodium droplets of 1.2 to 30 mm diameter were leaving the cell ceiling. The heating of cell gas in this manner resulted in an equilibrium pressure in the cell of ~ 3 psig. Work is continuing in this area to further refine the calculations and to study an extensive range of sensitive parameters.

Recent laboratory investigations^(3, 17, 19) with ~100 gram quantities of sodium injected into a 2 vol% oxygen atmosphere in a sealed tank with a spray nozzle resulted in pressure rises of 19.0, 14.1, and 5.1 psi. In the referenced tests the spray filled ~1/3 of the volume, about the same fraction to be expected under the most severe actual situation. In these tests, only the peroxide (Na_2O_2) reaction product was detected. This was to be expected since at the molar ratios reacting ($\text{Na}/\text{O}_2 = 2.1$) the product Na_2O_2 is predicted from free energy calculations. As a reasonable estimate of actual pressures at 1 vol% versus the 2 vol% test value, divide the theoretical pressure by the oxygen concentration, i.e., $19.0 \text{ psig} \div 2\% \text{ O}_2 = 9.5 \text{ psig}/\% \text{ O}_2$. The estimated pressures at 1 vol% oxygen are then: 9.5, 7.0, and 2.5 psig/% O_2 . All of these values are below the reactor equipment cell normal design pressure of 10 psig.

For the air case no clear mechanism appears available to produce spray fires in air filled containment spaces; primary sodium systems are located in inerted cells during reactor operation. During shutdown HTS sodium system pressures are reduced to the level (2 psig) where spray release potential can be regarded as hypothetical.

Variation of Parameters and Uncertainties

1. Pool Fires - One Cell Case

A number of studies have been completed for a closed inerted cell with low oxygen and the following base parameters:

Cell free volume	=	29,600 ft ³	Sodium spill	=	56,000 lb
Wetted floor area	=	980 ft ²	Sodium temp.	=	1050 °F
Wall area	=	7,340 ft ²	Burning surface	=	825 ft ²
			Oxygen concentration	=	1 vol%

The cell gas temperature and pressure will increase with increase in sodium spill, sodium temperature or burning surface. The temperature and pressure will decrease for an increase in volume, wetted floor or wall area. For a small increase in oxygen concentration there is a slight decrease in gas pressure and an increase in gas temperature; this pressure decrease is due to the net decrease in gas weight with increase in total oxygen consumption. This relationship is the same as recently reported by Atomics International⁽³⁾ for a parametric study of 2% oxygen pool fire analyses.

Table 4 indicates the results of varying the parameters: sodium spill quantity, sodium temperature and oxygen concentration. The conclusion from Table 4 is that for moderate changes in the base variables spill quantity and oxygen concentration there is negligible effect on gas pressure and temperature. The changes in cell pressure and temperature are significant only for a change in sodium temperature. This comparison indicates the dominating influence of sensible heat in the sodium at low oxygen concentrations.

The remaining variables: burning surface, volume, floor area and wall area are interdependent in that a change in one generally implies a change in all. As a comparison with the base case for which the maximum pressure was 5.47 psig and the maximum gas temperature was 287 °F the following alternate case is:

Cell free volume	= 32,000 ft ³	Max. pressure	= 4.8 psig
Wetted floor area	= 980 ft ²		
Wall area	= 7,340 ft ²	Max. gas temp.	= 264 °F
Burning surface	= 563 ft ²		

TABLE 4. Parametric Studies for Sodium Pool Fire in Closed Inerted Cells, Effect on Cell Pressure & Temperature

<u>Base Case Variable</u>			<u>Decrease in Variable</u>	<u>Increase in Variable</u>	<u>Rate of Change</u>
1.	<u>Sodium Spill Quantity (lb)</u>	56,000	45,000	65,000	
	Cell Pressure (psig)	5.47	5.01	5.81	+ 0.08 psi/1000 lb Na
	Cell Temperature (°F)	287	275	294	+ 1.90 °F/1000 lb Na
2.	<u>Sodium Temperature (°F)</u>	1050	900	1200	
	Cell Pressure (psig)	5.47	4.73	6.27	+ 1.03 psi/100 °F Na
	Cell Temperature (°F)	287	259	316	+ 38.0 °F/100 °F Na
3.	<u>Oxygen Concentration (vol%)</u>	1.0	0.5	2.0	
	Cell Pressure (psig)	5.47	5.53	5.35	- 0.12 psi/% O ₂
	Cell Temperature (°F)	287	285	290	+ 3.33 °F/% O ₂

The reduced maximum pressure is primarily a consequence of the smaller burning surface area.

TABLE 5. Effect of Sodium Spill Quantity on Peak Gas Temperature and Pressure for Closed Inerted HTS Cell Protected with Drip Pans and Insulation.

	<u>Decrease</u>	<u>Base</u>	<u>Increase</u>	<u>Rate of Change</u>
Sodium Spill (lbs)	45,000	56,000	65,000	
Peak Pressure (psig)	6.07	6.48	6.79	+0.036 psi/1000 lbs Na
Peak Temperature (°F)	315	324	331	+0.8°F/1000 lbs Na

For the closed inerted (1 vol% oxygen) HTS cell protected with drip pans and insulation a parametric study of sodium spill quantity is indicated in Table 5. Peak temperature and pressure is an increasing function of spill quantity as was the case for the non-insulated cell liner, Table 4.

For the one-cell case with low oxygen the primary heat source is the sensible heat of the sodium (~1050 °F initially), while the contribution from the heat of reaction is minimal in the low oxygen concentration. In this case the relatively hot sodium is always cooling down, the surface temperature is not different from that in the pool and the oxygen is consumed in approximately one hour.

2. Pool Fires - Two Cell Case.

For an HTS cell open to a larger secondary volume above, the base parameters include the following:

Cell free volume	= 29,600 ft ³	Sodium spill	= 50,000 lb
Secondary volume	= 1.3 million ft ³	Sodium temp.	= 500 °F
Cell wetted floor area	= 950 ft ²	Burning surface	= 825 ft ²
Cell wall area	= 7,370 ft ²	Oxygen concentration	= 21 vol%

All of the two cell parameters have the same effect on gas pressure and temperature as for the one-cell case with the exception of sodium spill quantity. For the above set of parameters the peak pressure increases for an increase in spill quantity up to a maximum pressure for 35,000 lb sodium; the peak pressure decreases for larger sodium spills. The reason for this is not directly related to the two cell configuration, but depends on the large excess supply of oxygen (which is not available in the closed, low oxygen cell). For spills of less than 35,000 lb the gas pressure reaches a peak at the time that sodium is consumed. For spills larger than 35,000 lb, the greater mass of relatively cool sodium (~500 to 800 °F) is a good heat sink for the oxidation reaction taking place at the surface (~1100 °F). The Maximum gas temperature occurs in the secondary containment volume for a spill of ~50,000 lb for this set of base parameters; the results of this study are indicated in Table 6.

Table 7 indicates the results obtained by varying the sodium spill quantity in the Reactor Head Cavity open to Outer Containment. The spill quantity was varied from 5,000 to 40,000 lbs and the max. pressure attained during each run was an increasing function of spill quantity over the range of spills tested. Still the peak pressure of 4.8 psig at 40,000 lb sodium spill is less than one-half the containment vessel design pressure of 10 psig.

TABLE 6. Parametric Study of Sodium Spill Quantities
for the Case: HTS Cell open to Outer
Containment

<u>Sodium Quantity (lb)</u>	<u>Peak Pressure (psig)</u>	<u>Time at Peak Pressure (hr)</u>	<u>Peak Temp in Shell (°F)</u>	<u>Time at Peak Temp in Shell (hr)</u>	<u>Time Sodium Consumed (hr)</u>
20,000	2.23	7.5	168	9.1	7.5
30,000	2.43	12.8	203	14.3	12.8
35,000	2.43	15.0	217	17.0	16.1
40,000	2.41	15.1	229	20.9	20.1
50,000	2.37	15.4	241	30.7	31.6
60,000	2.34	15.6	240	31.7	>35
100,000	2.19	16.6	238	33.3	>35
150,000	2.03	17.4	234	34.5	>50

TABLE 7. Parametric Study of Sodium Spill Quantities
for the Case: Reactor Head Cavity open to
Outer Containment

<u>Sodium Quantity (lb)</u>	<u>Peak Pressure (psig)</u>	<u>Time at Peak Pressure (hr)</u>	<u>Peak Temp in Shell (°F)</u>	<u>Time at Peak Temp in Shell (hr)</u>	<u>Time Sodium Consumed (hr)</u>
5,000	2.49	1.2	118	4.3	1.2
10,000	3.08	2.5	153	4.2	2.5
20,000	4.01	5.4	219	6.6	5.4
30,000	4.61	9.0	276	10.0	9.0
40,000	4.82	13.7	322	14.6	13.9

Uncertainties associated with the calculation of sodium pool fires are relatively small and are distributed between calculation method and preparation of input parameters. The calculation method⁽³⁾ has evolved from comparison with experimental results at Atomics International and agrees quite well for numerous one-cell cases modeled in the laboratory. Comparison shows that the calculated time history average for gas pressure and temperature varies from the experimental value within $\pm 5\%$. The two-cell case has not been modeled in the laboratory; however, work is now in preparation for an experimental investigation. The two-cell calculation includes the well-known buoyancy term in convective flow between the two cells, one located above the other. Conservative results have presently been assured by preparing conservative input parameters to the calculation.

2. Spray Fires

The primary variable affecting spray burning rate is the surface area of sodium. As with the pool fire, the burning rate increases with an increase in surface area. The surface area for fine particles may be higher by a factor of 10 to 1000 than for a pool fire for the same sodium release quantity. The burning rate is also an increasing function of the rate of arrival of oxygen at the burning surface. This burning rate is enhanced by the diffusion rate of oxygen, the velocity of ejected sodium, dispersal of sodium in the cell volume, the turbulence created by ejected sodium and the initial oxygen concentration. Increasing the sodium temperature also increases the burning rate. A high burning rate means a much higher heat transfer rate to the gas than from the gas to the walls, thereby allowing the gas pressure to build up in an initial spike.

A high leak rate for sodium will also increase the peak gas pressure; this is especially important in low oxygen since here the primary heat source is the sensible heat in the sodium itself. In either case a large sodium release will compress the gas further due to volume displacement in the closed cell.

Uncertainties related to spray fires are less predictable than for pool fires. Characterization of pipe breaks and leaks under accident conditions is important for these considerations. The rational approach indicates that it is highly improbable that a large volume release and fine particle spray dispersion could exist simultaneously. Experimental work⁽¹⁸⁾ (see Part B, Results section and Appendix B) has demonstrated that spray fire pressures in low oxygen environments are at least 40% less than the pressure calculated from thermal equilibrium. Much of the data (Appendix B) shows results much lower than this: The data spread is in the range of 5 to 60% of the maximum theoretical adiabatic value.

APPENDIX A

SODIUM POOL FIRE EXPERIMENTAL AND ANALYTICAL DEVELOPMENT

A sodium pool fire burns at the pool surface in contact with oxygen in the gas above it, the reaction rate depending upon the initial conditions in the sodium and in the cell gas and in the geometry and heat transfer properties of the structure. The SOFIRE-II computer code characterizes this burning condition with interaction factors determined from extensive laboratory experience.⁽⁵⁾⁽⁶⁾⁽¹⁷⁾⁽¹⁸⁾ Temperature readings in the pool, in the flame, and in the oxide smoke and gas mixture, along with heat balances between these components has been utilized to determine heat transfer coefficients and the gas interchange factor. The code includes heat transfer to adjacent walls and to interior heat storing masses. For the two-cell case convective flow between cells is determined by balancing buoyancy and velocity pressure terms (see SOFIRE-II model, Figure A-1).

The following data from a typical pool fire experiment⁽⁶⁾ gives an indication of conditions to be expected. A 4 ft deep x 2 ft diameter sodium pool initially heated to 350 °F was burned with a replenished air supply. Temperature in the pool increased from the bottom to a maximum of ~1100 °F at the surface. There was a sharp increase in temperature to 1800 °F in the flame immediately above the pool surface, which then dropped off asymptotically to ~500 °F at 6-in. above the surface. In this test an average sodium burning rate of 6 lb/hr-ft² was observed, the range was 3 to 10 lb/hr-ft² over a

FIGURE A-1 *SOFIRE-II Sodium Pool Fire Model*

32 hr period in which the solid oxide was building up from the pool bottom. The oxide finally extinguished the fire by forming a surface crust. For oxygen concentrations <5% the average burning rate observed is ~0.4 lb sodium/hr-ft² per 1% oxygen concentration.⁽³⁾

For the SOFIRE calculations with the closed vessel the peak temperature and pressure in the gas is attained after 1 hr in a small cell (50,000 ft³) to over 10 hrs of burning in a large vessel (~1 million ft³).

Recent developments in pool fire tests at Atomics International⁽¹⁷⁾ indicate that large fractions of both the monoxide Na₂O and peroxide Na₂O₂ are produced as reaction products. A test in air resulted in 70% peroxide formation while a later test⁽¹⁸⁾ in 10% oxygen produced 70% monoxide. Preliminary results indicate that pool burning in 2 vol% oxygen produces nearly 100% sodium peroxide, no monoxide having been detected in the case investigated.

APPENDIX B

SODIUM SPRAY FIRE EXPERIMENTAL AND ANALYTICAL DEVELOPMENT

In 1956 Hines and Kelley⁽¹³⁾ reported results for spray oxidation in various oxygen concentrations of 0.6 to 21%. Peak pressures ranged from 8 psig at 0.6% oxygen to a maximum of 38 psig in air. This work, in support of Fermi FBR, utilized commercial nozzles and a drive pressure of 360 psi to inject 1 lb of sodium at 850 °F into a 532 liter container. The sodium-oxygen ratio was 4.7:1 with 21% O₂ and the total time for injection was ~25 seconds.

In 1958 Humphreys⁽¹⁴⁾ reported results for rapid injection of varying amounts of sodium (0.5-4:1 Na/O₂ molar ratio) into air by the detonation of a hydrogen-oxygen gas mixture. The volume of the cylindrical reaction vessel was 2032 liters and sodium was 750 °F. The maximum pressure, 85 psig, occurred for a molar ratio of 3:1 while a maximum of 75 psig occurred at a ratio of 4:1 (see Figure B-1). Sodium ejection times were on the order of 3 to 10 msec. This work was in support of EBR-II.

In 1960 Gracie and Droher⁽⁵⁾ reported results on spray oxidation in low oxygen concentrations (0 to 5%) in a 48 ft³ rectangular chamber. One-half pound of liquid sodium at 1000 °F and 50 psig drive pressure was injected through a slit ~.002-in. wide. Maximum pressure rise in 2% oxygen was 1.8 psig at a molar ratio Na/O₂ = 9:1. This work was performed in support of SRE.

FIGURE B-1 *Adiabatic Pressures for Sodium-Air Reaction*

In 1966 Leibowitz, et al,^(7,10) determined theoretical maximum pressures and temperatures resulting from sodium-oxygen thermal equilibrium in air. The calculations gave results similar to those determined by other investigators^(8,9) and utilized the method of free energy minimization^(11,12) to predict the product ratios. Results of this study are compared with other investigations in Figure B-1.

In 1965 Charak and Smith⁽¹⁵⁾ reported on a brief series of tests in which 1 or 2 g quantities of sodium at 1200 °F were fired from a revolver into an air-filled chamber where the Na/O₂ ratio was 4:1. The maximum pressure rise recorded was ~80 psig.

In 1966 Krolikowski⁽¹⁶⁾ reported results of sodium injection at high velocity, 1000 to 1500 psig drive pressure, into a 16.7 liter chamber. Ten grams of liquid sodium at 800 °F was injected through a set of small orifices (0.01 to .03-in. diam) into various oxygen concentrations from 3.8 to 21 vol%. Maximum pressure rise in air was 45 psig at a Na/O₂ molar ratio of 3:1, while pressure rise was 3.8 psig in 3.8% oxygen at a molar ratio of 17:1.

Work on an analytical model to be used within a computer code to predict the results of spray burning is in progress at Atomics International.⁽¹⁹⁾ The variables to be dealt with are: sodium particle size (affects burning surface area), velocity and rate of ejection, fraction of cell volume covered by spray, sodium temperature, diffusion of oxygen and concentration of oxygen. Testing of the analytical model is done with experiments performed in the Spray Test Vessel (see Part B in Results section).

In this series of tests 20 to 80 gm quantities of liquid sodium were driven by 20 to 100 psig through a 15° cone spray nozzle into a 31.4 ft³ test vessel in from 1 to 20 seconds. A comparison of heat and mass balances indicated that adiabatic conditions were maintained during the spray period. The lowest oxygen concentration tested in this series was 4.6 vol% (test no. 6); a pressure of only 2.9 psig was measured. Only 8% of the oxygen and 12% of the sodium was consumed and the pressure was ~10% of the theoretical maximum.

Later tests in this series (Test No's. 9 and 10) produced measured pressures of 19.0, 14.1 and 5.1 psig for spray into 2 vol% oxygen. Here mass balances indicated a higher efficiency of combustion, 35% of the sodium and 50% to 100% of the oxygen was consumed.

The conclusion from this series of tests at AI is that the maximum attainable pressures for spray fire in low oxygen is primarily dependent on the mixing efficiency achieved for the sodium and oxygen reactants and result in pressures of ~60% of theoretical.

APPENDIX C

EFFECT OF OXIDE DEPOSIT ON CELL WALLS ON HEAT TRANSFER CAPABILITY

An investigation of oxide plating on walls of a cell in which sodium oxide from a sodium fire is being circulated by natural convection has shown that the effect on heat transfer coefficient is negligible. In a closed inerted HTS cell with 1 vol% oxygen assume all 23 lbs of oxygen are consumed by sodium fire. Assume that only monoxide has been formed; this gives 89 lbs of oxide vs. only 56 lbs if the product is peroxide. If all of the monoxide is assumed airborne the result is 4.45 ft^3 of monoxide or an average deposit thickness of 7.3 mils. The plate out on HTS cell walls not wetted with sodium is $\sim 7000 \text{ ft}^2$ of surface assuming an oxide density of 20 lb/ft^3 ⁽²¹⁾. The heat transfer coefficient of the oxide film is then:

$$h = \frac{K}{L} = \frac{0.52}{.00073} = 710 \text{ Btu/ft}^2\text{-hr-}^\circ\text{F}$$

where $K = 0.52 \text{ Btu/ft-hr-}^\circ\text{F}$ ⁽²¹⁾

The natural convection coefficient from gas to wall is in the range of $1\text{-}5 \text{ Btu/ft}^2\text{-hr-}^\circ\text{F}$; therefore the minimum overall heat transfer coefficient through gas plus oxide film is then:

$$h_o = \frac{1}{\frac{1}{5} + \frac{1}{710}} = 4.965$$

The conclusion is that the effective decrease in heat transfer coefficient from cell gas to cell wall liner steel surface is <1%. This analysis assumes that 100% of the oxide is airborne and that all is plated out on the walls. This proves to be quite conservative since pool fire tests in 2% oxygen⁽¹⁷⁾ indicate that only about 40% of the oxide becomes airborne and that much of this falls back into the pool.

REFERENCES

1. R. P. Johnson. SOFIRE I-B Sodium Fires Code, TI-707-14-001. Atomics International, Canoga Park, California, February 1969.
2. J. L. Anderson. Chemical Equilibrium Calculations, Program E-194. Argonne National Laboratory, Argonne, Illinois, March 1966. (Converted to UNIVAC 1108 Fortran V as NAFIRE, November 1968).
3. R. P. Johnson, et al. Sodium Fires Study for FFTF Preliminary Safety Analysis Report, AI-69-MEMO-96. Atomics International, Canoga Park, California, November 14, 1969.
4. "Sodium Coolant Ejection Studies", FFTF Monthly Informal Technical Progress Report, BNWL-1274, p 10.6. Battelle-Northwest, Richland, Washington, November 1969.
5. J. D. Gracie and J. J. Droher. A Study of Sodium Fires, NAA-SR-4383. Atomics International, Canoga Park, California, October 1960.
6. G. N. Lauben. "Initial Experience with Large Sodium Fires Experiments (LF-1)", NAA-SR-12041, Atomics International Canoga Park, California, August 1966.
7. L. Leibowitz. "Sodium-Air Reactions", Fast Reactor Safety Studies, Chemical Engineering Division Semiannual Report January-June 1966, ANL-7225, p 201. Argonne National Laboratory, Argonne, Illinois, June 1966.
8. E. Garelis and J. B. Nims. Sodium-Air Accident Study for a Sodium Cooled Reactor, AECU-4164. Division of Technical Information Extension, Oak Ridge, Tennessee, July 1959.
9. L. Baker and A. D. Tevebaugh. "Sodium-Air Reaction Calculations", Reactor Safety, Chemical Engineering Division Annual Report, January-June 1965, ANL-7055, p 208. Argonne National Laboratory, Argonne, Illinois, October 1965.
10. L. Leibowitz. "Calculations for the Sodium-Air Reaction", Reactor Development Program Progress Report June 1966, ANL-7230. Argonne National Laboratory, Argonne, Illinois.

REFERENCES (Continued)

11. W. B. White, S. M. Johnson and G. B. Dantzig. "Chemical Equilibrium in Complex Mixtures", Journal of Chemical Physics, vol. 28, p 751, 1958.
12. R. C. Oliver, S. E. Stephanou and R. W. Baier. "Calculating Free-Energy Minimization," Chemical Engineering, vol 69, no. 4, p 121. February 19, 1962.
13. E. Hines and J. K. Kelley. Determination of the Maximum Pressures Obtained During the Reaction of Sodium with Air in Closed Systems NP-7320. Detroit Edison Company, February 1956.
14. J. R. Humphreys, Jr. "Sodium-Air Reactions as they Pertain to Reactor Safety and Containment", Proceedings of Second International Conference on Peaceful Uses of Atomic Energy, Geneva, vol 22, p 177. 1958.
15. I. Charak and F. A. Smith. "Preliminary Evaluation of a Technique to Study Expulsion of Sodium into Air", Proceedings of Conference on Safety, Fuel and Core Design in Large Fast Power Reactors, ANL-7120, p 868. Argonne National Laboratory, Argonne, Illinois, October 1965.
16. T. S. Krolikowski. Violently Sprayed Sodium-Air Reaction in an Enclosed Volume, ANL-7472. Argonne National Laboratory, Argonne, Illinois, September 1968.
17. H. A. Morewitz, et al. Annual Technical Progress Report, LMFBR Safety Programs, GFY 1969, AI-AEC-12858 (Health and Safety), Atomics International, Canoga Park, California, October 15, 1969.
18. H. A. Morewitz, et al. Quarterly Technical Progress Report, LMFBR Safety Programs, January-March 1970, AI-AEC-12947 (Health and Safety), Atomics International, Canoga Park, California, May 15, 1970.
19. H. A. Morewitz, et al. Annual Technical Progress Report, LMFBR Safety Programs, GFY 1970, AI-AEC-12970 (Health and Safety), Atomics International, Canoga Park, California, August 15, 1970.
20. M. W. First and H. Yusa, "Heat Transfer of Sodium Compounds Deposited on Surfaces from Aerosols," pp. 413-424, Proceedings of the Eleventh AEC Air Cleaning Conference, Richland, Washington August 31-Sept. 3, 1970, CONF 700816, Vol. 1.