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SODIUM FIRE PROTECTION BY
SPACE ISOLATION, OPEN CATCH
PAN AND NITROGEN FLOODING --
FFTF PROOF TEST F5

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FFTF PROOF TEST F5

W. D. Boehmer

R. K. Hilliard

October, 1975

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SODIUM FIRE PROTECTION BY
SPACE ISOLATION, OPEN CATCH
PAN AND NITROGEN FLOODING --
FFTF PROOF TEST F5

W. D. Boehmer
R. K. Hilliard

ABSTRACT

A large-scale sodium fire extinguishment test was performed to demonstrate the adequacy of the FFTF secondary sodium fire protection system. Twenty-three hundred pounds of sodium at 1100°F were spilled into an air filled cell which had a steel catch pan protecting the concrete floor and walls. The fire was self-extinguished when the oxygen in the relatively leak tight cell was consumed by sodium-oxygen reaction. Nitrogen flooding was started after 15 minutes to maintain an inert atmosphere during cooling. Only 5.7% of the sodium was reacted during the test. Approximately 100 lb. of water were released from the concrete, one tenth of which reacted to form hydrogen. It was concluded that all aspects of the test results were predictable and that the FFTF secondary sodium fire protection system was verified.

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SODIUM FIRE PROTECTION BY SPACE ISOLATION,
OPEN CATCH PAN AND NITROGEN FLOODING--
FFTF PROOF TEST F 5

INTRODUCTION

The secondary sodium equipment and piping in the Fast Flux Test Facility (FFTF) are located in an air atmosphere. Although the probability of a large sodium spill is extremely low, a fire protection system is being provided which is capable of controlling and extinguishing sodium fires involving several thousand gallons of sodium. The system consists of space isolation, open catch pans, and nitrogen flooding. In a few specific locations this system is augmented by a drainage sump equipped with a perforated cover plate.

Space isolation is achieved by providing walls, partitions, fire doors, ventilation dampers and penetration seals to form relatively small (less than 20,000 ft³) isolatable rooms. If a sodium spill should occur, the affected room is isolated automatically by closing the ventilation dampers upon a signal from smoke detectors. The burning sodium is allowed to consume all the available oxygen in the room, and combustion is automatically terminated when the room oxygen content is exhausted.

Steel catch pans are located under all sodium piping and equipment. These pans protect the concrete floor and walls from direct contact with the sodium pool formed by the spill. The pans are open-topped and have sufficient depth to contain the largest possible spill. Steel wall-to-pan shrouds guide any sodium sprayed onto the walls into the pan. The pans are "free floating;" i.e., they rest directly on the concrete floor and are not anchored to the concrete.

Pressure relief vents are provided to prevent overpressurization. During the first few minutes after a sodium spill, heat from the burning sodium is transferred to the cell atmosphere, causing an expansion and escape of smoke through the pressure relief vent and other cell leakage paths. Although space isolation features are automatic, operator action

is required to activate the nitrogen flooding system. If the operator decides to initiate nitrogen flooding, nitrogen flow is started by manually attaching a nitrogen supply hose to a line leading to the affected cell and opening a manual valve. The flow is adjusted to approximately one cell volume per hour and maintained at a constant rate until the sodium has cooled. The purpose of the nitrogen is not to purge the space free of oxygen, but to maintain a slight positive cell pressure to prevent in-leakage of oxygen.

Four large-scale proof tests have been performed to verify the FFTF secondary sodium fire protection system. The tests were performed in the Large Sodium Fire Facility (LSFF) at the Hanford Engineering Development Laboratory (HEDL). Test F1 demonstrated the need for concrete protection by showing that a large spill of sodium directly onto a concrete surface resulted in complete reaction of the sodium, extensive damage to the concrete, and high concentrations of hydrogen in the cell atmosphere⁽¹⁾. Steel liners and catch pans have been installed in all FFTF sodium areas to eliminate direct sodium-concrete reactions in the event of a spill.

Test F2 demonstrated that a combination of space isolation and nitrogen flooding was effective in controlling and extinguishing a large sodium fire when no concrete was present^(2, 3). The sodium in test F2 was spilled into a steel pan which rested on insulating firebrick within an all-steel cell.

The third test (F4) showed that a covered sump, with nitrogen injected into the space beneath the coverplate, was very effective in preventing combustion of the sodium which entered the sump⁽⁴⁾. The cover plate contained two 1-inch diameter holes per ft². Sodium which did not drain into the sump, but remained in the outer cell area, was completely oxidized. The only covered sumps in the FFTF secondary sodium areas are piping trenches in each of the three secondary pump cells.

A fourth test (F5) was performed on April 16, 1975. The purpose of test F5 was to verify the final design of the FFTF sodium fire protection system in ex-containment areas other than the secondary pump cells. The

conditions of this test were also similar to those which would occur in the pump cells in the event of a massive spill which would overflow the covered pipe trench. The results of test F5 are the subject of this report.

SUMMARY AND CONCLUSIONS

Sodium fire protection features typical of those provided in FFTF ex-containment sodium spaces were mocked up and tested against a large sodium spill. The chief features were an open sodium catch pan, space isolation by a cell mockup structure, nitrogen flooding, and a mockup of a cell piping penetration seal. Approximately 2300 pounds of 1100°F sodium were spilled into the open catch pan which rested directly on the concrete floor. The resulting pool was 110 square feet in area and five inches deep. The simulated pipe break was effected by discharging the sodium through an open ended 3-inch ID pipe at a distance of six feet above the pan. The sodium flow rate was approximately 300 gal/min, a portion of which was directed against one of the cell walls. The duration of the sodium spill was 1.1 minutes. The effects of the ensuing fire were monitored, including temperatures in the concrete, sodium, and cell atmosphere; concentration of oxygen, hydrogen and water vapor in the cell atmosphere; differential pressure across the cell wall; nitrogen flood flow rate; and sodium oxide aerosol concentration. At the end of the test a material balance was made and the fraction of sodium reacted and the amount of water released from the concrete were determined.

Data obtained during test substantiate the following observations and conclusions:

- The FFTF sodium fire protection system for ex-containment sodium cells and pipeways was demonstrated to be effective in controlling and extinguishing large sodium fires, as evidenced by the rapid cooling of the sodium pool, the small amount of smoke released from the cell, the lack of damage to the concrete or cell structure, and the safe concentration levels of hydrogen and oxygen.
- Approximately 5.7 percent (133 pounds) of the spilled sodium reacted during the test. About 24 pounds of this sodium directly reacted with water released from the test concrete. The balance reacted with the oxygen present in the test atmosphere. A

portion of the reaction product formed during the sodium-oxygen reaction subsequently reacted with water to form sodium hydroxide.

- The free-floating steel catch pan effectively prevented a direct concrete-sodium reaction. The pan was warped slightly, but its integrity was maintained. The wall-to-pan interface shroud was effective in guiding all of the sodium sprayed on the walls into the pan. No sodium was exposed directly to the concrete.
- Approximately 100 pounds of water were released from the concrete floor and partial walls even though they were protected from direct contact with the sodium. The moisture release rate was highest during the initial 7-hour period, when the concrete temperatures were increasing, but moisture continued to be released at a diminishing rate from 7-hours until monitoring was terminated 45 hours after the spill. The specific water release was 0.63 pounds of water per square foot of concrete. This compares closely with the value of 0.65 determined in test F4. It is probable that if a larger quantity of sodium had been spilled, resulting in a deeper pool, that additional water would have been released from the concrete. It is also probable that more water would have been released if the concrete had extended over all the interior surfaces of the cell.
- Approximately one-half lb-mole of hydrogen was formed by reaction between the water released from the concrete and the sodium in the catch pan. This represents 0.1 mole of hydrogen formed per mole of water released. The balance of the water either reacted with the sodium oxide formed by the air oxidation of sodium or was swept out of the cell by the nitrogen flood gas.
- The hydrogen concentration was essentially zero during the initial 10-minute period after the sodium spill, when the oxygen concentration was above 5 percent. After 10 minutes, it increased rapidly to a maximum value of 3.7 volume percent at one

hour. At that time, the oxygen concentration was 0.5 percent. At no time during the test was there a combustible mixture of hydrogen and oxygen in the cell atmosphere (greater than 4 percent hydrogen, greater than 5 percent oxygen). However, after the nitrogen flood gas flow was stopped, the oxygen concentration increased to approximately 9 percent, at which time the hydrogen concentration was 2 percent. Continuation of the nitrogen flood beyond the minimum period used for this test would have maintained the oxygen and hydrogen concentrations at negligible levels.

- The oxygen concentration did not decrease to as low a value as in previous tests and increased fairly rapidly after the nitrogen flood period. It is postulated that Na_2O_2 was the chief product of reaction between sodium and air during the early stages of the fire, especially during the spill when the splashing caused a large sodium surface-to-volume ratio. Later, when moisture from the concrete became available, the Na_2O_2 reacted with the water to release oxygen.
- The differential pressure (DP) across the cell wall reached a maximum of 0.34 inches of water during the spill. The maximum DP occurred only 3 seconds after the first sodium entered the cell. The pressure relief vent was held open during the spill period, giving 6.3 square feet of open vent area. The calculated venting rate of heated air and smoke during the spill reached a maximum of 10,000 cubic feet per minute. Enclosed cells should be equipped with adequate pressure relief vents to accommodate high venting rates during the very rapid pressure transients associated with large sodium spills.
- Approximately one pound of smoke particles was released from the cell during the test. This represents only 0.05 percent of the mass of sodium spilled, and shows the good smoke retention capability afforded by the cell structure.

- The sodium chilled from 1100°F in the supply tank to 970°F at one minute after the start of the spill. It then heated to a maximum of 1040°F at 2 minutes. It then cooled continuously until it reached the freezing point 7 hours after the spill. This was faster cooling than in any of the previous tests and shows that heat conduction into the concrete was significant.
- The concrete reached a maximum surface temperature of approximately 500°F on the floor, 360°F on the wall. The concrete temperature exceeded the normal boiling point of water at depths to nearly 3 inches in the floor, 1.5 inches in the wall.
- The average temperature of the cell atmosphere increased very rapidly to 750°F at the end of the sodium spill. This was a considerably greater temperature increase than in previous tests and was caused by the large surface area of the pool and the more rapid heat transfer to cell atmosphere from the splashing sodium. Previous tests used anti-splash devices to minimize spray drop formation. The temperatures were fairly uniform throughout the cell volume, showing that convection was good.
- The cell piping penetration seal, fabricated of silastic rubber impregnated with fiberglass, survived the test without leaking. It attained a maximum temperature of 555°F. Only a few small isolated drops of sodium splashed onto the surface. In pre-test experiments, specimens of the same material were completely destroyed by spraying sodium onto them, indicating that the seal would fail if it were contacted directly by large amounts of liquid sodium.
- After the sodium pool cooled to room temperature, it was found to consist of fairly pure sodium metal with an approximately 1/8-inch thick top crust of crystalline sodium hydroxide covered by a thin layer of concentrated sodium hydroxide solution. The solid sodium hydroxide was effective in preventing further reaction between the sodium and the water in the sodium hydroxide solution.

- The 2400 pounds of waste sodium were removed satisfactorily by cutting into small chunks with pneumatic tools.

TEST CONDITIONS

EXPERIMENTAL PROCEDURE

The procedure followed for Test F5 was to simulate a major sodium spill in a typical FFTF secondary HTS cell initially containing normal air. Approximately 350 gallons of hot molten sodium was spilled rapidly into a typical steel catch pan resting on concrete. About 90% of the sodium was spilled directly into the catch pan. The remaining 10% of the spill was directed against the test cell wall and flowed down the wall, over a steel run-off plate, and into the catch pan. Temperatures, pressures, and concentrations of oxygen, hydrogen, and moisture were monitored and recorded. Videotape recordings were made of events that occurred during the test.

To protect the test cell from damage by pressure produced during the sodium spill, the pressure relief vent installed in the test cell wall was propped open. Pretest calculations revealed that rapid expansion of the test cell atmosphere, due to heat transfer from droplets produced during the spill, in combination with the inertia of the relief vent (set to open at 2 in. H_2O) could produce a pressure differential greater than the test cell design limit of 4 in. H_2O . The vent was closed immediately following the completion of the sodium spill.

The nitrogen flooding system was activated 15 minutes after the sodium spill. When the sodium pool temperature had decreased to 400°F, the nitrogen flood was terminated. After the sodium had reached the freezing point, a low flow of nitrogen was supplied to the test cell to limit the moisture entering prior to sampling. After the sodium temperature had decreased below 100°F, the test cell was entered for inspection and sampling. The frozen sodium was removed from the catch pan and the pan was removed from the concrete section. The concrete was sampled to determine moisture content. After all the samples had been taken and the inspections had been completed, the concrete was removed for disposal.

TEST EQUIPMENT

Description of the Fire Facility

A description of the Large Sodium Fire Facility (LSFF) has been given in previous reports^(1, 2). Briefly, the testing is performed inside a ventilated concrete fire room. A test cell has been installed in the fire room and sodium spills are performed inside the cell.

Sodium is charged from 400-pound drums to a "batch tank" in an adjacent room. Electrical heating of the sodium to the desired test temperature is done in the batch tank and the sodium is discharged to the test cell by pressurizing the batch tank and opening a valve on the discharge line. Figure 1 is a plan view of the LSFF work area. Figure 2 is a conceptual diagram of the test cell fire area.

The leak rate of the test cell was measured before the test at 160 SCFM at 0.42 in. H₂O differential pressure. The locations of thermocouples, gas sample points and aerosol sample points are presented in Appendix A.

HTS Cell Mockup

Features of the FFTF secondary Heat Transport System (HTS) cells were incorporated into the test article for Test F5. These features included an open sodium catch pan and a cell piping penetration seal. Figure 3 is a schematic drawing of the catch pan and the splash run-off plate installed in the reinforced concrete test section. The catch pan and splash plate were fabricated from 3/16-inch carbon steel plate (ASTM A-36) and the pan size was 13.3 x 8.3 x 1 foot high. The pan was installed with a nominal 1-inch gap between the sides of the pan and the 2-foot high concrete walls. The splash run-off plate was attached to the concrete walls with a lip overlapping the top of the catch pan. The splash plate was not sealed to the catch pan and this gap allowed water vapor released from the concrete to escape into the test cell atmosphere. Figure 4 is a photograph of the catch pan after it had been installed in the cell.

Figure 5 is a drawing of the piping penetration seal as it was installed for the test. The fiberglass-reinforced silastic rubber seal

FIGURE 1. Plan View of LSFF Work Area.

FIGURE 2. Conceptual Diagram of Test Cell.

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FIGURE 3. Catch Pan and Run-off Plate Details.

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FIGURE 4. Photograph of Catch Pan After Installation.

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FIGURE 5. Piping Penetration Seal Details.

material was fastened to a 34-inch diameter dummy pipe and to a wall penetration sleeve with steel straps and adhesive. The seal was installed at an elevation high enough to prevent nearly all direct sodium contact, but was subjected to the test cell atmosphere temperature and the full pressure differential between the interior and exterior of the cell. Figure 6 is a photograph of the seal.

Concrete Properties

The cells and pipeways in the FFTF are constructed of reinforced concrete, with wall thicknesses of several feet. Since the test cell mockup is fabricated of 16-gage steel sheetmetal, the concrete feature of FFTF cells was simulated by pouring a concrete floor and partial walls within the test cell, using the test cell metal walls as the outer form. Figure 7 is a drawing of the concrete test section and Figure 8 is a photograph taken before installation of the catch pan.

The concrete was mixed at the FFTF batch plant to the same specifications used in the actual FFTF secondary HTS structures. It was type C1-p with 3/4-inch basalt aggregate and SiO_2 sand. The composition of the concrete at the time of mixing is given in Table I. The total mass of concrete poured was 32,500 lb.

TABLE I
CONCRETE COMPOSITION

	<u>lb/ft³</u>	<u>wt %</u>
Portland cement	18.3	12.3
Sand (SiO_2)	54.5	36.6
Aggregate (3/4-in. basalt)	66.8	44.9
Water	9.11	6.12
AEA	0.01	0.008
WRA	0.06	0.042
TOTAL	<u>148.8</u>	<u>99.97</u>

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FIGURE 6. Photograph of Dummy Piping Penetration Seal.

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FIGURE 7. Concrete Test Section Details.

FIGURE 8. Photograph of Concrete Test Section Before Installation of Catch Pan.

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The 12-inch thick floor had aged 56 days by the time the test was performed. The 9-inch thick walls were poured 5 days later and had aged 51 days by the time of the test. A one-foot cube was poured from each truckload of concrete to serve as a control specimen for moisture analysis.

Two coats of epoxy sealant were applied to the inner surfaces of the concrete after the concrete had cured for 28 days. The pan was installed 3 days later.

Nitrogen Flooding System

The nitrogen flooding system consisted of a liquid nitrogen storage tank and atmospheric evaporators capable of supplying up to 200 SCFM of nitrogen gas. A 1-1/4-inch pipe delivered the nitrogen to the interior of the test cell, with the terminus at 10 feet above the catch pan bottom. The flow was controlled using a manual 1-1/4-inch globe valve and the rate was measured with a flowmeter and recorded with a strip chart recorder. During the nitrogen flooding period of the test, the flow rate was maintained at 48 SCFM.

TEST CONDITIONS

A summary of the test conditions are listed in Table II.

TABLE II
SUMMARY OF TEST CONDITIONS FOR TEST F5

Mass of sodium spilled	2330 $\pm$ 30 lb
Sodium temperature prior to spill	1100 $\pm$ 20°F
Sodium temperature 2 minutes after completion of spill	1040°F
Duration of spill flow	66 sec
Average spill flow rate	300 gal/min
Batch tank cover gas pressure prior to spill	14 psig
Test cell gas volume	2480 ft ³
Test cell floor area	150 ft ²
Test cell wall and ceiling material	16 ga C-STL
Test cell floor material	1/4-in C-STL
Test cell insulation	1-in. fiberglass blanket, k=0.025 Btu/hr-ft-°F @150°F
Test cell leak rate	160 SCFM @0.42 in. H ₂ O @70° F
Concrete	FFTF type C1-p, 51-day minimum cure time, sealed with epoxy coating, 12-in. thick floor, 9-in. thick walls, 2-ft high above floor.
Catch pan	Open top, installed free directly on concrete floor, 1-in. gap between pan and walls, 3/16-in. C-STL, 13.3 x 8.3 x 1-ft high, 110 ft ² surface area.
Piping penetration seal	Fiberglass reinforced silastic rubber, 1/16-in. thick, mounted on 34-in. OD dummy pipe and 46-in. ID sleeve, pipe centerline 10 ft. above cell floor.
Extinguishing method	Space isolation, O ₂ depletion by reaction with sodium, N ₂ flood to prevent O ₂ reentry.
N ₂ flooding system operation	Start flow of 48 SCFM at 15 min after sodium spill, stop flow when sodium temp. decreases to 400°F.
Large fire room total volume	11,620 ft ³
Large fire room floor area	553 ft ²
Ventilation flow through fire room	5000 SCFM
Temperature of fire room inlet air	62 $\pm$ 2°F
Dewpoint of fire room inlet air	40 $\pm$ 2°F
Barometric pressure	29.47 $\pm$ 0.02 in. Hg
Total air flow to scrubber	10,000 SCFM

RESULTS AND DISCUSSION

NARRATIVE OF EVENTS

The first evidence of sodium entering the cell occurred 3 seconds after the 3-in. sodium spill valve operator was activated. Film from a 16-mm motion picture camera operating at 4 times normal speed showed that a small quantity of sodium was first discharged, possibly less than one gallon. After a fraction of a second of hesitation with no flow, the full pipe diameter flow began. A significant fraction of the flow broke into droplets, but the main discharge could be seen for ~10 seconds as a fairly cylindrical column with a wavy surface. Perhaps 5% of the total flow broke into drops. The drops rebounded off the pan bottom and side in oblique upward directions. Estimation of droplet size is extremely uncertain, but the pretest estimate of 1/4-inch diameter drops appeared reasonable. Figures 9 and 10 are photographs made from frames taken from the motion picture film taken during the spill. Figure 9, taken approximately one second after full flow began, shows the spray drops, many of which are traveling upward. Figure 10, taken approximately 4 seconds after the full flow of the spill began, shows the spilling column of sodium and the dense smoke clouds which soon obscured the view.

The spill lasted 1.1 minutes. The maximum pressure of 0.34 in. H₂O was attained 3 seconds after the sodium first reached the cell atmosphere. The cell gas temperature increased very rapidly, reaching ~750°F average at the end of the spill. The cell vented with a rapid flow which pressurized the outer fire room and injected smoke into the operating gallery. Visibility in the fire room decreased to <5 ft. The fire room ventilation fan continued to exhaust the room at 5000 CFM and the visibility improved to a ~20 ft five minutes after time zero.

The sodium temperature dropped from 1100°F to an average of 970°F immediately after the end of the spill. The sodium temperature increased to a maximum of 1040°F in two minutes, then decreased for the remainder of the test.

When the nitrogen flood began at 15 minutes after the spill, smoke again vented from the cell. The differential pressure, which had

FIGURE 9. Sodium Spray Drops During Spill--Test F5.

69101-2

FIGURE 10. Sodium Stream Discharge and Smoke Formation During Spill.

69101-1

decreased to zero, rose to 0.26 in. H_2O , where it remained for the duration of the nitrogen flood.

The oxygen concentration decreased rapidly until it was 5% in 11 minutes. Hydrogen was not detected until the oxygen was <5%. Hydrogen then increased to a maximum of 3.7% at one hour after the spill.

The nitrogen flood was terminated 138 minutes after the spill, when the sodium pool was 395°F and the average cell gas temperature was 280°F. Both the oxygen and hydrogen concentrations began to increase when the nitrogen flood stopped, reading maximum values of 9% oxygen and 2% hydrogen. A low nitrogen purge (16 SCFM) was started 7.5 hours after the spill, to prevent moisture from entering the cell from the exterior atmosphere, and continued to 46 hours after the spill. At this time the cell was ventilated for 25 minutes and then entered for inspection and sampling. After sampling was completed, the residual sodium was removed from the catch pan, the pan was cut up and removed, and the test concrete was broken up for disposal.

A detailed narrative of events is given in Appendix B.

RESULTS DURING FIRE PERIOD

Nitrogen Flooding System Performance

The nitrogen flooding system was activated 15 minutes after the initiation of the sodium spill and was terminated 123 minutes later. The flow remained very stable at the predetermined rate of 48 SCFM. The temperature of the nitrogen gas delivered to the test cell remained nearly constant at 68°F during the flooding period. Only 5900 SCF of nitrogen was used during the flooding period. 37,000 SCF of nitrogen was used during the slow purge from 7.5 hours to the time that the cell was opened.

Sodium Temperatures

The temperatures at five depths in the sodium pool are plotted in Figure 11 for the first 40 minutes following the sodium spill. Figure 12 presents the long-term temperature history for the sodium pool, cell

FIGURE 11. Sodium Pool Temperature at Various Depths.

FIGURE 12. Long-Term Temperature History.

atmosphere and concrete floor. During the spill, the sodium was chilled from a temperature of 1100°F to an average temperature of 970°F. This temperature compares favorably with a predicted chill temperature of 962°F. The predicted chill temperature was calculated assuming instantaneous heat transfer from the 1100°F sodium to the spill pipe and steel catch pan initially at room temperature and negligible heat of reaction added during the sodium spill.

The temperature gradient in the 5-inch deep sodium pool was fairly linear and had a value of approximately 40°F/inch during the first few minutes. The gradient was reduced rapidly as the concrete beneath the pan heated and the burning rate at the sodium surface decreased until, at 15 minutes after the spill, temperature equilibrium in the sodium pool was reached.

As shown in Figure 11, a sudden rapid decrease was recorded in the signal from a thermocouple near the sodium pool surface at about 15 minutes after the spill. It is suspected that at this time warpage of the catch pan caused the thermocouple to be raised from within the sodium pool to a position above the pool surface where it sensed the somewhat cooler atmosphere temperature.

The sodium increased in temperature from 970°F immediately after the spill to a maximum of 1040°F one minute later, and then cooled at a nearly constant rate of 9°F/min for the next 40 minutes. The pool reached the freezing temperature (208°F) 6.5 hours after the spill and underwent a 4-hour isotherm during freezing. The cooling rate of the pool during this test was considerably more rapid than in previous tests. Test F2, which had a 5-inch deep pool in a steel pan resting on insulating brick, reached the freezing point in 10 hours and required 6 hours to freeze. Test F4, which had a 16-inch deep pool in a steel-lined concrete sump with a coverplate, reached the freezing point in 10 hours and required an additional 10 hours to freeze. The pool in Test F5 cooled more rapidly because it lost heat both to the atmosphere above and to the concrete below.

Concrete Temperatures

The temperatures of the concrete floor of the test article at various depths are plotted in Figure 13 with the average sodium pool temperature included as a reference. The concrete wall temperatures at various depths adjacent to the sodium pool are plotted in Figure 14. There was less heat transferred from the sodium pool to the concrete walls than to the floor because of the nominal 1-inch gap between the walls and the catch pan. The long-term temperature of the concrete floor at 1-inch depth is plotted in Figure 12 to 46 hours after the spill.

The concrete was heated to the normal boiling point of water to a depth of nearly 3 inches in the floor and to about 1.5 inches in the walls.

Test Cell Atmosphere Temperatures

The temperatures of the test cell atmosphere at six elevations from near the sodium pool surface to near the test cell ceiling are plotted in Figure 15 for the first 40 minutes following the sodium spill. Near the sodium pool, a maximum temperature of 915°F was reached and near the test cell ceiling the maximum temperature was 775°F. An average gas temperature of 754°F was attained during the sodium spill. The gas then cooled rapidly to an average temperature of 472°F and was subsequently reheated to an average of 490°F at 15 minutes after the sodium spill. After this temperature was reached, continuous gradual cooling followed. The long-term temperature history is shown in Figure 12.

Figure 16 shows the temperature of the surface of the silastic rubber piping penetration seal exposed to the interior of the test cell. The average cell atmosphere temperature is shown as a reference. The maximum temperature experienced by the seal was 555°F and occurred during the sodium spill.

Pressure Differential

Calculations performed prior to the test indicated that the pressure transient associated with the sodium spill would be significantly greater

FIGURE 13. Temperature of Concrete Floor at Various Depths.

FIGURE 14. Temperature of Concrete Wall at Various Depths.

FIGURE 15. Temperature of Test Cell Atmosphere.

FIGURE 16. Temperature of Silastic Rubber Piping Penetration Seal.

than in previous tests. The increase in the rate of pressure buildup was expected because: (a) the sodium pool surface area was larger in Test F5 by a factor of 3.6; and (b) considerable splashing of sodium was expected in Test F5 because of the 6-ft free-fall onto the pan surface. In all prior tests, spray formation was essentially eliminated by extending the spill pipe to within a few inches of the pan and providing an anti-splash device.

The calculations showed that the rate of expansion of the cell gas due to heat transfer from the hot sodium was sensitive to the assumed spray drop size and volumetric flow. In order to provide a basis for estimating these important spill characteristics, the spill was mocked up by flowing water at 300 gal/min from a 3-inch pipe onto a concrete floor from a 6-ft elevation. Figure 17 shows a closeup view of the sheet of water and droplets formed near the floor. It was estimated that approximately 50% of the water rebounded from the floor. Some drops formed near the 3-inch pipe and fell the entire distance. The maximum bounce height was 4 feet, but most of the splatter was confined to less than 2 feet. The average drop size was estimated to be 1/4-inch diameter.

Because the surface tension of sodium at 1100°F is twice that of room temperature water⁽⁵⁾, the assumption was made that only 10% of the sodium spill in Test F5 would form 1/4-inch diameter monosize drops. Other assumptions were that the heat transfer to air was adiabatic, only convective heat transfer occurred, the drops and falling column of sodium would react at a rate of 24-lb Na/hr ft² to form Na₂O₂, and that the expansion was at constant pressure. A maximum venting rate of 3200 ft³/min was calculated to be required to maintain constant pressure. Alternatively, if the test cell pressure relief vent failed to open rapidly, the initial rate of pressure buildup would be 0.3 psi/sec.

Installed in the test cell used in Test F5 was a counterbalanced, 5-bladed, louvered pressure relief vent (PRV) which began to open at 1-in. H₂O differential pressure (DP). The variable area feature of this PRV causes difficulty in predicting the DP which would result from any

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FIGURE 17. Water Simulation of Spray Drop Formation.

given venting rate above the pretest leak rate data. An estimated curve is shown as a broken line in Figure 18. The two sloping straight lines were calculated from the standard orifice equation:

$$Q = CA \left(\frac{244 g DP}{\rho} \right)^{0.5} \quad (1)$$

where Q = vent flow rate, ft^3/sec

C = flow coefficient, dimensionless

A = vent area, ft^2

g = gravitational constant = 32.2 ft/sec^2

DP = differential pressure, lb/in^2

ρ = density of gas, lb/ft^3

The data of Figure 18 are for steady-state conditions. Another characteristic of the counterbalanced PRV which causes uncertainty in predicting pressure pulses is the inertia of the PRV blades. For rapid gas expansions, such as predicted for Test F5, the DP would probably attain values above that predicted in Figure 18. The $3200 \text{ ft}^3/\text{min}$ maximum venting rate estimated from heat transfer calculations would give a DP of 3.5-in. H_2O at steady-state, after the PRV had time to open. Because inertia might have caused the DP to exceed the 4-in. H_2O design pressure, the decision was made to prop the PRV wide open for the test and close it immediately after the spill was completed.

A maximum DP of 0.34 in. H_2O was measured 3 seconds after the first evidence of sodium reaching the test cell atmosphere. The DP is plotted for the early moments of the test in Figure 19. The DP fell rapidly to zero after reaching the maximum. The observed DP of 0.34 in. H_2O resulted from a venting rate of $12,000 \text{ ft}^3/\text{min}$, according to Figure 18. This is a factor of four greater than predicted from heat transfer considerations. Because of the uncertainties in the calculations, this agreement is considered reasonable. A test observation that substantiates the higher venting rate is the fact that the large fire room attained a positive pressure for a few seconds immediately after the beginning of the spill. Since the room was being ventilated at a rate of 5000 SCFM by an exhaust

FIGURE 18. Steady State Differential Pressure As A Function of Cell Venting Rate.

FIGURE 19. Differential Pressure at Early Times.

fan, the cell venting rate must have exceeded 5000 ft³/min.

The longer-term data for differential pressure are plotted in Figure 20. After the sodium spill was complete and the PRV was closed, the DP attained a maximum negative value of -0.64 in. H₂O. Gas leakage into the cell reduced the DP to zero within a few minutes. When the nitrogen flood was started, the DP rose and remained at a relatively constant value of 0.26 in. H₂O throughout the flood period. The DP fell to zero when the nitrogen flood was terminated and subsequently rose to a small positive value when the low nitrogen purge was introduced. The nitrogen purge of 16 SCFM continued until the cell was opened for inspection.

Cell Gas Analysis

Mass Spectrometric Analysis - Ten grab samples were drawn from the test cell atmosphere and one was taken from the outer fire room ventilation exhaust duct at specified times during the test. These samples were analyzed by mass spectrometry and the results are shown in Table III. These results made possible comparison with the on-line gas sampling analyses for oxygen and hydrogen and yielded information on other components of the atmospheres tested.

FIGURE 20. Long-Term Differential Pressure.

TABLE III

MASS SPECTROMETER ANALYSIS RESULTS OF CELL ATMOSPHERE

Time after spill (min)	→	3	10	20	35	38	50	68	120	240	362	606
Sample Pt. No.*	→	1	1	2	1	4	1	2	2	1	2	1
Component												
O ₂		11.9	5.49	1.69	0.85	20.7	0.66	0.12	0.06	4.04	7.09	2.75
H ₂		<0.01	0.16	0.85	2.81	0.02	3.24	3.33	1.24	1.67	1.77	0.48
N ₂		86.6	92.7	95.9	95.4	78.3	95.5	96.1	98.5	93.4	89.7	95.8
CO ₂		<0.01	<0.01	<0.01	<0.01	<0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ar		1.44	1.55	1.39	0.80	0.94	0.53	0.36	0.20	0.82	1.43	0.97
CO		<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
He		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CH ₄		0.02	0.08	0.13	0.09	0.01	0.07	0.04	0.03	0.02	0.02	0.02

* Refer to Appendix A for sample point locations.

Oxygen Concentration - The concentration of oxygen in the test cell atmosphere is plotted in Figure 21. Mass spectrometric results are plotted for comparison with the results of the on-line analyses. Sample gas was drawn from two locations within the test cell; sample point 1 was 6 inches above the sodium pool surface. Sample point 2 was near the test cell ceiling.

The oxygen concentration decreased to less than 5% within 11 minutes after the sodium spill and to less than 1% within 45 minutes. After about 140 minutes, when the nitrogen flood to the test cell had been terminated, the oxygen concentration began to increase. This result may be explained by the following possible mechanisms:

- Oxygen was released by reaction of sodium peroxide with water, according to Equation (2).
- $$\text{Na}_2\text{O}_2 + \text{H}_2\text{O} \rightarrow 2 \text{NaOH} + 1/2 \text{O}_2 \quad (2)$$
- Chimney effect due to the elevated temperature of the gas enclosed in the cell induced circulation of outside air through small leak paths at different elevations.
 - Cooling of the cell atmosphere caused reduced pressure and inleakage of air.
 - The concentration gradient between the test cell atmosphere and the room air in the outer fire room caused diffusion of oxygen into the cell.

The first two of these postulated mechanisms are believed responsible for most of the observed oxygen increase. The reaction of Equation (2) could have been catalyzed by ionic iron, which was found to be present in significant quantities as a result of corrosion of the catch pan and cell walls. Since oxygen buildup was much faster than in Tests F2 and F4, in which there was no opportunity for the peroxide-water reaction, this mechanism is believed to be the major contributor in Test F5.

The oxygen concentration increased to a maximum of approximately

FIGURE 21. Oxygen Concentration in Test Cell Atmosphere.

9% at 7.5 hr, at which time the slow nitrogen purge was started. The oxygen concentration then decreased and remained at <1% for the remainder of the test.

Hydrogen Concentration - The concentration of hydrogen in the test cell atmosphere is plotted in Figure 22. Mass spectrometric results are plotted for comparison with the on-line analyses.

The hydrogen concentration reached a maximum about 60 minutes after the sodium spill. Significant discrepancies are evident when the maximum concentrations indicated for each of the two sample points are compared to one another and to the mass spectrometry results. The mass spectrometry results are considered most reliable and indicate that the maximum hydrogen concentration in the test cell was about 3.7 mole %. The average of the results from the two on-line analyses indicate a maximum of 5% hydrogen. Moisture is believed to have introduced error in the on-line hydrogen analyzer, which used the thermal conductivity of the cell gas as a measure of hydrogen concentration. It had been calibrated with dry nitrogen. After reaching the peak level, the hydrogen concentration decreased rapidly to 1% by the time the nitrogen flood to the test cell was terminated.

To determine the approximate quantity of hydrogen produced during test F5, the results from the two on-line sample points were averaged. This average concentration is plotted in Figure 23. Integration of this curve with respect to the instantaneous nitrogen flooding rate yields the information that 0.52 lb-mole of hydrogen was produced. Assuming the reaction which produced the hydrogen proceeded according to the following equation:

there was a one-to-one ratio of moles of water reacted to moles of hydrogen formed. Therefore, 0.52 lb-mole (9.4 pounds) of water were reacted.

FIGURE 22. Hydrogen Concentration in the Test Cell Atmosphere.

FIGURE 23. Long-Term Moisture and Hydrogen Concentrations.

Moisture in Cell Atmosphere - The concentration of water vapor in the test cell atmosphere was monitored by passing a sample of gas drawn from the cell through a flow probe containing a hygrometer. Figure 23 shows the long-term moisture data plotted with the average hydrogen concentration included as a reference. Initially, the moisture content of the cell atmosphere was reduced, probably due to absorption of water on sodium oxide aerosol particles and on the sodium combustion products plated on interior test cell surfaces. At about 12 minutes after the sodium spill, the moisture began to increase as water was driven from the test concrete. A first maximum of 0.0033 pound H_2O per pound of dry gas (5800 ppm) was reached at 35 minutes then began to decrease again as the reaction of water with sodium took place and produced hydrogen. After the hydrogen concentration reached the maximum level and had begun to decrease, the moisture concentration began to increase again at a very rapid rate.

For the period of time from 140 to 450 minutes after the sodium spill, erroneous readings were observed at the output of the hygrometer. It is believed that this was caused by condensation of water vapor in the sample line, which was at room temperature. This occurred because the dew point of the cell atmosphere was above room temperature. Liquid water was observed in the sample line and rotometer.

To determine the total water swept from the test cell by the nitrogen flood and later, by the slow nitrogen purge, the moisture curve in Figure 23 was integrated with respect to the instantaneous nitrogen flow rate. This calculation showed that 1.8 pounds of water escaped the test cell during the initial nitrogen flood and that 21.7 pounds escaped during the slow purge, for a total of 23.5 pounds of water released from the cell as vapor.

Sodium Oxide Aerosol

The sodium oxide aerosol concentrations in the test cell atmosphere, the outer fire room and the ventilation exhaust is plotted in Figure 24. The maximum concentration in the test cell was about $10g/m^3$ (STP) as Na

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FIGURE 24. Sodium Oxide Aerosol Concentration.

and occurred approximately 12 minutes after the sodium spill. For purposes of comparison, maxima of 18g/m^3 , 13g/m^3 , and 5g/m^3 were reported for previous fire tests F1, F2, and F4, respectively. After the peak level was reached, the sodium oxide aerosol concentration decreased rapidly with a half life of approximately 11 minutes. This corresponds to fallout by stirred settling of $10\text{ }\mu\text{m}$ diameter aerosol particles.

The aerosol concentration in the outer fire room averaged 6% of that inside the test cell for the first 3 hours following the sodium spill.

Smoke Abatement

Approximately 580g (expressed as Na) of sodium oxide/hydroxide smoke particles escaped from the cell during the test. Of this, approximately 105g deposited in the large fire room, 55g deposited in the ventilation tunnel, 150g were removed by the scrubber, 160g were removed by the filters and 110g was released to the 250-ft stack. The scrubber efficiency was 36%; the filter efficiency 60%. The low scrubber efficiency is probably due to the small particle sizes. Most of the larger particles had settled out during the two minute transit time to the scrubber. Higher concentration would increase agglomeration to larger particle sizes where the scrubber would be more effective. The low filter efficiency is believed due to leaky gaskets in the 12-year old installation.

The release to the environment was only half that released in Test F2, but 10 times the release in Test F4. The release in Test F5 was approximately 0.1% of established guidelines⁽⁸⁾.

POST TEST EXAMINATION

General Observations

The test cell was opened for inspection at 46 hours after the sodium spill. The catch pan and splash run-off plate were intact and the residual sodium pool was contained by the catch pan. Reaction products, predominantly gray-white in color, formed a hard crust covering the sodium pool and were present on interior test cell surfaces. A thin layer of sodium

hydroxide solution covered the crust on the sodium pool. A view of the test cell interior and sodium pool surface is shown in Figure 25.

A rust pattern on the test cell wall indicated that the portion of the sodium spill directed from the 1-inch auxiliary pipe had flowed down the wall, over the run-off plate, and into the catch pan. The piping penetration seal was intact and had withstood the test conditions.

Sodium Residue

The residual sodium was sampled by driving 3/4-inch core sampling tubes down through the pool. The crust on the sodium pool surface varied in thickness from 1/8 to 3/8-inch and the predominantly metallic bulk of the pool was approximately 4.5-inches thick. The results of chemical analyses for constituents of the residual sodium pool are summarized in Table IV.

A sodium mass balance was prepared from the results of the chemical analyses using estimates of the quantities of residual sodium and reaction products that remained in the sodium pool, that adhered to test cell surfaces, and that had escaped from the test cell. The sodium was cut into small pieces and weighed. The results of this mass balance are shown in Table V and a summary of the chemical forms are shown in Table VI. A total of 2354 pounds of sodium were accounted for, which is within 1% of the 2333 pounds actually charged to the batch tank for the spill. Of this total, 133 pounds or 5.7% was reacted. Approximately 84.7 pounds (3.6%) formed NaOH, 27.5 pounds (1.2%) was found as Na₂O, and 21.1 pounds (0.9%) was Na₂CO₃.

Approximately 102 pounds of water were associated with the reaction products inside the test cell. An additional 24 pounds were swept from the cell during nitrogen flow and 9 pounds were reacted to form hydrogen. The total quantity of water accounted for was 135 pounds.

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FIGURE 25. Post-test View of Test Cell Interior Immediately After Opening for Inspection.

TABLE IV
COMPOSITION OF RESIDUAL SODIUM POOL

	Crust		Excluding Crust		Total Pool	
	lb	%	lb	%	lb	%
Metallic Sodium	0	0	2221	98.4	2221	93.3
NaOH	81.8	67	0.9	0.04	82.7	3.5
Na ₂ O	0	0	36.1	1.6	36.1	1.5
Na ₂ CO ₃	7.3	6	0.3	0.015	7.6	0.3
H ₂ O	28.1	23	0	0	28.1	1.2
Fe	4.9	4	0.1	0.003	5.0	0.2
Total	122	100	2258	100	2380	100.0

TABLE V
SODIUM MASS BALANCE - TEST F5

	Mass, lb.	Metallic Na		NaOH		Na ₂ O		Na ₂ CO ₃		H ₂ O		Fe	
		%	lb	%	lb	%	lb	%	lb	%	lb	%	lb
Sodium Pool ^(a)	2380	93.3	2221	3.5	82.7	1.5	36.1	0.3	7.6	1.2	28.1	0.2	5.0
Cell Surfaces	150	0	0	42.3	63.5	0	0	27.3	41.0	27.0	40.5	3.4	5.1
Escaped from Cell	25.5	0	0	4.3	1.1	3.5	0.9	0	0	92.2	23.5 ^(b)	0	0
Total	2555.5	86.9	2221	5.8	147.3	1.4	37.0	1.9	48.6	3.6	92.1	0.4	10.1

(a) From Table IV

(b) From Section 4.2.6.4

TABLE VI
SUMMARY OF CHEMICAL FORMS

Chemical Form	Total		Equivalent as Na		Equivalent as H ₂ O
	1b ^(c)	%	1b	%	1b
Metallic Na	2221	86.9	2221	94.3	0
NaOH	147.3	5.8	84.7	3.6	33.1
Na ₂ O	37.0	1.4	27.5	1.2	0
Na ₂ CO ₃	48.6	1.9	21.1	0.9	0
H ₂ O	92.1	3.6	0	0	92.1
Fe	10.1	0.4	0	0	0
Total	2555.5	100.0	2354.3	100.0	125.2

(c) From Table V.

After all sampling had been completed, the residual sodium was removed from the catch pan using pneumatic guns and spade tools. The method of removal is shown in Figure 26. A coating of lightweight oil was maintained on all exposed surfaces of the sodium to limit further reaction with oxygen and moisture. Removal of the predominantly metallic sodium in 4 x 6 x 5-inch deep bricks proved to be the most effective method of cleanup.

Steel Catch Pan

Figure 27 shows the steel catch pan after the residual sodium had been removed. The pan had suffered some warping, but all welds remained intact and no sodium had penetrated the pan. The bottom of the pan had warped upward in the center to approximately 3/8-inch above the concrete floor. The sides of the pan had warped outward an average of 0.3-inch around the top. The sodium removal operation had caused superficial scratching of the steel pan.

The wall-to-pan splash run-off plates were effective in preventing any entry of sodium to the space between the pan and concrete surfaces.

Concrete Test Section

From visual inspections, the test concrete was not damaged by the test conditions. During the post-test sodium removal operations, however, the use of pneumatic tools caused minor chipping of the concrete floor beneath the catch pan in areas where the impacting of the tools was transmitted through the bottom of the pan. The epoxy sealant on the concrete surfaces suffered minor charring during the test from contact with the hot catch pan. This charring occurred in a few isolated locations, as shown in Figure 28.

Piping Penetration Seal

Figure 29 is a post-test view showing the piping penetration seal. Examination of the silastic rubber seal material revealed that it was not damaged by test temperatures and pressures, but received a few minor surface burns from drops of sodium splashed onto it during the spill. The seal intentionally had been installed at a high elevation in the test cell

FIGURE 26. Removal of Residual Sodium with Pneumatic Tools.

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FIGURE 27. View of Sodium Catch Pan After Removal of Residual Sodium.

FIGURE 28. View of Concrete Surface After Removal of Catch Pan.

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to limit direct contact with sodium. A layer of $\text{NaOH}/\text{Na}_2\text{CO}_3$ particles coated its surface. Pre-test sodium spray experiments performed on samples of the seal material showed that contact with hot sodium causes extensive burning of the silastic rubber and embrittling of the fiberglass reinforcing material. Figure 30 shows the damage that resulted when a 12 x 12-inch piece of the seal material was sprayed with a small quantity of 900°F sodium in an air atmosphere.

Moisture Loss from Concrete

The 12-inch cube concrete control specimens were sampled at various depths one day before the test was performed. The moisture content of the samples was measured to provide a basis for estimating the initial water content in the test article concrete. The method used to determine the moisture content of all samples was to measure the difference in mass of the sample before and after heating. The samples were heated to a temperature of 800°C (1472°F) which is sufficiently high to drive off all of the chemically bound water as well as the free water in concrete.

Following the removal of the catch pan and the completion of visual observations, the concrete test article was sampled at several locations in the floor and the walls. Samples were taken from six depths in the concrete floor and from four depths in the walls. All sampling of the walls was done at an elevation of four inches above the floor surface, approximately 1-inch below the level where the adjacent sodium pool surface had been.

In Figures 31 and 32 are plotted the results of the moisture analyses for the floor and the wall concrete, respectively. The plots show that the moisture content for the first 4 inches of depth was significantly less for the post-test samples compared to the moisture content of the control samples for both the floor and wall locations. Results for the control specimens closely matched the post-test sample results for depths greater than 4 inches, averaging 6.2 wt. % water for the floor and 6.4 wt. % water for the walls.

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FIGURE 30. Damage to Silastic Rubber Seal Material by Sprayed Sodium.

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FIGURE 31. Moisture Content of Concrete Floor.

FIGURE 32. Moisture Content of Concrete Walls.

The approximate quantity of water lost from the test article concrete was calculated from the difference between the moisture content of the control specimen and test article samples which was obtained from integration of the curves in Figures 31 and 32. The results are summarized in Table VII and show that a total of 70 pounds of water were released from the concrete. This amount is considerably less than the 135 pounds of water accounted for by chemical analysis of the reaction products. The two methods used to determine the quantity of water released are subject to errors encountered both in chemical and moisture analyses and in estimations and averages. In addition, it is probable that some moisture from the ambient air entered the concrete during the 4-day period between the test and the time when the concrete samples were taken. This would cause the calculated moisture loss by the concrete to be erroneously low. Likewise, absorption of moisture from room air during sodium sampling would cause the Table VI water balance to be erroneously high. Taking these factors into consideration, it is believed that 100 ± 30 pounds of water were released from the concrete. This results in about 0.63 ± 0.19 pounds of water released per square foot of exposed concrete surface area.

The release of water from concrete as a function of time and temperature was determined in laboratory tests by grinding approximately 1-pound samples taken from the FFTF batch plant test cylinders. Two types of concrete were analyzed: conventional (basalt and SiO_2) used in test F5, and magnetite (FFTF type M-225). The samples were broken with a hammer into particles ranging from dust to 3/4-inch-diameter maximum size and placed in a controlled temperature tube with a dry nitrogen gas flow. Moisture released from the concrete was stripped from the sweep gas by desiccant traps and weighed periodically. Figure 33 plots the concrete weight loss as a function of time at room temperature and several higher temperatures. Diffusion limited mass transfer from concrete to sweep gas is clearly indicated by the decreasing release with time. It is noteworthy that for the conventional concrete a significant release, 3.75 percent weight loss ($5.5 \text{ lb H}_2\text{O}/\text{lb concrete}$), occurred at room temperature

FIGURE 33. Moisture Loss From Concrete Exposed to Dry Nitrogen as a Function of Time.

TABLE VII
WATER LOSS FROM CONCRETE TEST ARTICLE

	<u>Floor, concrete</u>		<u>Wall, concrete</u>	
	<u>0-4 in.</u>	<u>>4 in.</u>	<u>0-4 in.</u>	<u>>4 in.</u>
Water content of control (wt, %)	5.8	6.2	5.9	6.4
Water content of test article (wt, %)	4.9	6.2	5.0	6.4
Loss (wt, %)	0.9	0	0.9	0
Concrete weight (lb)	5625	11,300	2160*	2700
Water loss (lb)	50.6	0	19.4	0

*Because of the gradient of temperature from the bottom to the top of the 24-inch-high walls, the lower 12 inches of the walls were considered to have the full loss shown and the upper 12 inches were considered to have zero loss.

in these zero humidity measurements. This is approximately half of the total water content of the concrete. The rate data in Figure 33 cannot be used directly for calculating water release under sodium fire conditions because the atmosphere in actual cases would probably have an appreciable water vapor content which would reduce the rate of diffusion. However, the figure does show the potential for large water loss at low temperatures if the atmospheric humidity is kept at a low value, e.g., by reaction with sodium vapor.

The effect of temperature on water release from concrete is shown more clearly in Figure 34. High-density (magnetite) concrete released significantly less water at room temperature but was more dependent on temperature. The broken line shown in Figure 34 is taken from Hilsdorf⁽⁷⁾ and represents generalized data available in the literature for conventional concrete with a water/concrete ratio of 0.5.

FIGURE 34. Water Loss from Concrete as a Function of Temperature.

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APPENDIX A

TABLE A-1

THERMOCOUPLE LOCATIONS - SODIUM FIRE TEST F5

TC No.	Recorder Point	Remarks	Location
1	C1	a	Concrete floor, center, surface
2	C2	a	Concrete floor, center, 1" below surface
3	C3	a	Concrete floor, center, 3" below surface
4	C4	a	Concrete floor, center, 6" below surface
5	C5	a	Concrete floor, center, 9" below surface
6	C6	a	Concrete floor, center, 12" below surface
7	C7	b	Concrete east wall, surface
8	C8	b	Concrete east wall, 1" beneath inner surface
9	C9	b	Concrete east wall, 3" beneath inner surface
10	C10	b	Concrete east wall, 6" beneath inner surface
11	C11	b	Concrete east wall, 9" beneath inner surface
12	C12	g	Concrete north wall, 1" beneath inner surface
13	G1	g	Concrete south wall, 1" beneath inner surface
14	G2	d	Concrete floor, 11.5' from north wall of test cell, 1" deep
15	G3	d	Concrete floor, 3.5' from north wall of test cell, 1" deep
16	G4	c	Concrete east wall, 1" below surface
17	G5	e	Air gap between pan and concrete, east wall, 16" above cell floor
18	F1	a	Sodium pool, center, 0.25" above pan bottom
19	F2	a	Sodium pool, center, 1.5" above pan bottom
20	F3	a	Sodium pool, center, 2.5" above pan bottom
21	F4	a	Sodium pool, center, 3.75" above pan bottom
22	F5	a	Sodium pool, center, 4.75" above pan bottom
23	F6	e	Sodium pool, 1" from center east wall, 2.5" above pan bottom
24	D Red	e,f	Sodium pool, 3" from center east wall, 2.5" above pan bottom
25	G6	a	Cell air over center of pan, 5.5" above pan bottom
26	D Blue	a	Cell air over center of pan, 6.5" above pan bottom
27	G7	a	Cell air over center of pan, 8" above pan bottom
28	G8	a	Cell air over center of pan, 11" above pan bottom
29	G9	a	Cell air over center of pan, 17" above pan bottom
30	E1	a	Cell air over center of pan, 3.5' above pan bottom
31	E2	a	Cell air over center of pan, 9' above pan bottom
32	E3	a	Cell air over center of pan, 16' above pan bottom
33	E4		Cell air, 2' from north cell wall, 5' from east wall, 3' above pan bottom
34	E5		Cell air, 2' from north cell wall, 5' from east wall, 16' above pan bottom
35	E6		Cell air, 2' from south cell wall, 5' from east wall, 16' above pan bottom
36	E7		Touching silastic rubber boot on pipe penetration
37	E8		Air, inlet to large fire room
38	E9		Air, ventilation exhaust duct from large fire room
39	H-1		Exhaust fan discharge
40	I-1		Scrubber outlet air
<p>a 4' from east cell wall, 7.5' from north cell wall</p> <p>b 7.5' from north cell wall, 1'-4" above cell floor</p> <p>c 2' above steel floor of cell</p> <p>d 4' from east cell wall</p> <p>e 7.5' from north cell wall</p> <p>f 1/8" sheath TC (all other TC's are 1/16" sheath)</p> <p>g 14.5" above steel floor of cell</p>			

TABLE A-2
GAS SAMPLE POINT LOCATIONS

<u>Sample Pt. No.</u>	<u>Location</u>
1	Near Na pool, 2 ft above cell floor, 4'6" from south wall, 1'6" from west wall
2	16 ft above mockup floor, 5 ft from west wall, 4 ft from north wall
3	Spare. 4'6" above cell floor, 6" from south wall, 5' from west wall
4	In exhaust air duct from the large fire room.

TABLE A-3
AEROSOL SAMPLE POINT LOCATIONS

<u>Point Number</u>	<u>Location</u>
1	Large fire room, 9' above floor, 6" from west wall of mockup, 7' from north wall of mockup
2	Mockup, 12' above floor, 6" from west wall
3	Exhaust fan discharge
4	Between scrubber and HEPA filter bank
5	Downstream of HEPA filters

TABLE A-4
PRESSURE SENSOR LOCATION

Located 11'9" above cell floor, extending 1' into the cell at the centerline of the south wall

FIGURE A-1. Instrument Sensor Locations.

APPENDIX B
NARRATIVE OF EVENTS

<u>Time After Sodium Spill Was Initiated</u>	<u>Event</u>
-15. min.	Sodium batch tank pressurization began (14 psig reached at -13.5 min), sodium temperature = 1100°F.
0	Spill valve opened.
3 sec	First evidence of sodium spill recorded by TV camera. A small quantity of sodium spurted from the 3-inch spill pipe, followed by a brief pause with no flow.
4.5 sec	First evident of test cell differential pressure (DP). Main flow of sodium spill from 3-inch pipe and lesser flow from 1-inch pipe recorded by TV camera.
7.5 sec	Maximum test cell DP during spill attained, DP = 0.34 in. H ₂ O. Smoke rushed out propped-open pressure relief vent and filled outer fire room.
72.5 sec	Batch tank reached zero gage pressure. Prop pulled to close relief vent. Maximum average temperature of test cell atmosphere (greater than 3-foot elevation) reached 754°F. Maximum surface temperature of piping penetration seal reached 555°F.
3 min	Zero visibility in outer fire room. Temperature of sodium pool near surface = 1070°F, near pan bottom = 975°F, average of 6 points = 995°F. Average cell atmosphere temperature = 473°F, oxygen concentration (average 2 points) = 11.4%,

NARRATIVE OF EVENTS (Cont'd)

Time After Sodium Spill Was Initiated

Event

hydrogen concentration (average 2 points) = 0%,
DP = -0.02 in. H₂O.

5 min Visibility improved in outer fire room. Average sodium pool temperature = 984°F, average cell atmosphere temperature = 464°F, oxygen concentration = 9.2%, hydrogen concentration = 0%.

11 min Smoke exiting relief vent visible.

15 min Nitrogen flood (48 SCFM) began. Smoke exiting vent increased. Buckling of catch pan near center indicated by rapidly falling temperature reading of T/C just under sodium pool surface. T/C probably raised out of pool. Average sodium pool temperature = 883°F, average cell atmosphere temperature = 473°F, oxygen concentration = 3.9%, hydrogen concentration = 0.12%, DP = 0.28 in. H₂O.

30 min Smoke exiting vent decreased. Visibility improved in outer fire room. Average sodium pool temperature = 749°F, average cell atmosphere temperature = 461°F, oxygen concentration = 1.08%, hydrogen concentration = 1.98%, DP = 0.18 in. H₂O.

60 min Maximum hydrogen concentration (average 2 points) reached 5.03%, oxygen concentration = 0.48%. Maximum temperature of 1-inch-deep concrete reached 275°F in floor, 235°F in wall. Smoke exiting vent decreased to intermittent wisps. DP = 0.21 in H₂O.

NARRATIVE OF EVENTS (Cont'd)

Time After Sodium Spill Was Initiated

Event

138 min	Nitrogen Flood ceased. Average sodium pool temperature = 395°F, average cell atmosphere temperature = 280°F, oxygen concentration = 0.17%, hydrogen concentration = 0.82%.
180 min	Oxygen and hydrogen concentration levels increased since nitrogen flood ceased. Oxygen concentration = 1.20%, hydrogen concentration = 1.57%.
270 min	Hydrogen concentration leveled at 1.99% (average 2 points), oxygen concentration = 3.94%.
450 min	Nitrogen flow (16 SCFM) to test cell began, to prevent moisture entering cell. Average sodium pool temperature = 205°F (approximate freezing point of sodium), average cell atmosphere temperature - 153°F, oxygen concentration = 9.4%, hydrogen concentration = 1.78%, DP - 0.02 in. H ₂ O.
46 hr	Ventilating air flow through test cell began. Average sodium pool temperature = 95°F.
46 hr 25 min	Test cell door opened and sampling began.
47 hr 12 min	Sampling completed.
47 hr 35 min	Sodium removal begun. Removal required approximately 9 hours.
6 days	Catch pan removed, concrete sampled and disposal began.

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