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EXPERIMENTAL EVALUATION OF
CELL LINERS

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EXPERIMENTAL EVALUATION OF
CELL LINERS

ABSTRACT

Cell liners may be used in breeder reactor sodium pipe ways, sodium cells, and lower cavity region to provide a leak-tight cell and to protect the concrete from sodium in the unlikely event of a sodium spill. The objectives of the HEDL liner verification test program are to evaluate the integrity of liner concepts under postulated accident conditions and to develop the experimental data base which will demonstrate that liners will not fail. Two specific tests are reported; a high temperature liner feature test, and a large-scale liner sodium spill test. In both tests no failures of the liners or tendencies toward failure were detected. The discussed liner designs appeared to be conservative, and the liner strength appeared to be more than adequate.

1.0 INTRODUCTION

Cell liners may be used in breeder reactor designs in sodium pipe ways, sodium cells, and the lower cavity region for essentially two reasons. First, they provide a leak tight cell which is or may be inerted, and second, they provide protection of the concrete from sodium in the unlikely event of a sodium spill. In accident or safety analysis a breach in the sodium coolant system may be hypothesized. For the resulting postulated accident conditions continued integrity of the cell liners may be desirable or in some situations essential. It is therefore important to understand and determine the consequences of the hypothesized accidents on cell liners.

For safety assessment, it is customary to assume a most conservative approach in determining the effects from an unlikely accident. In this conservative approach, cell liners may be assumed to partially or totally fail. However, if sufficient data were available which would demonstrate that cell liners would not fail under assumed accident ^{conditions} ~~conditions~~, or local failures would still provide sufficient protection to limit sodium concrete reactions, then more credit could be given for the presence of cell liners. A more realistic safety assessment of the consequences of such an accident could then be determined.

The breeder reactor safety technology program plan involves a protection-in-depth approach. A major program goal is to develop a technology base of both analytical tools and experimental data which will demonstrate reactor safety. In support of this plan, the major objectives of the HEDL liner verification test program are to evaluate the integrity of liner concepts under postulated accident conditions and to develop the experimental data base which will demonstrate that liners will not fail. The basic design objectives of a liner system are assumed to be

- 1) a liner configuration which remains intact during a coolant leak and allows no leakage of coolant to the structural concrete or leakage of gases,

- 2) a reliable steam venting system which will not plug and allow over-pressurization,
- 3) thermal protection of the structural concrete if that is necessary to maintain adequate structural strength,
- 4) a configuration which is reasonably inexpensive to construct.

The HEDL test program discussed in this paper is presently concerned with the scenario where hot sodium is allowed to impinge on cold steel liners under prototypic accident conditions. Other test programs address the question of the involvement of molten core debris in the lower cavity region.

Two specific tests will be discussed. They are the high temperature liner feature test, FT-3, and the large-scale liner sodium spill test, LT-1. For discussion here a "Liner System" will consist of the following basic essential components:

- 1) the structural concrete of which the cell is constructed,
- 2) the leakproof liner to protect the structural concrete from leaked coolant,
- 3) the venting system to allow escape of steam released from the concrete when heated.

2.0 SUMMARY

The two HEDL tests have included two wall design configurations and one floor configuration. One test involved rapid heating of a wall segment by radiant heating so that visual observations were possible. In the second test, liquid sodium was actually spilled on a liner and the resulting sodium pool was heated to just below the sodium boiling temperature and allowed to cool. No failures of the liners or tendencies toward failure have been detected in the tests. The liner designs appeared to be conservative and liner strength appeared to be more than adequate. Both tests showed that concrete behind the liners, especially in the vicinity of embedded steel structures, fractured due

to the effects of rapid heating. The fracturing of the concrete was only at the surface and no adverse consequences of the fracture were observed.

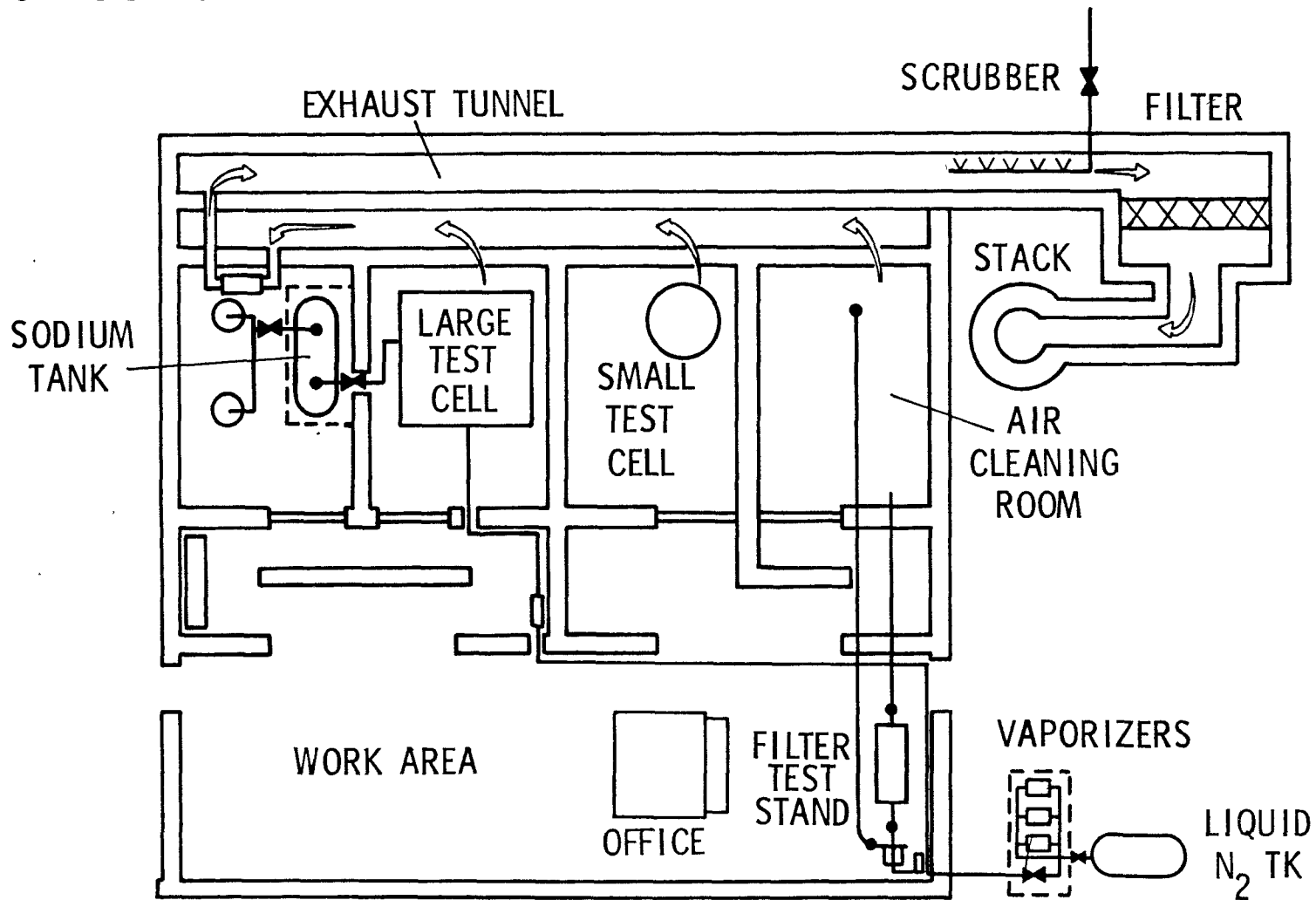
3.0 TEST FACILITY DESCRIPTION

The HEDL Large Sodium Fire Facility (LSFF) is a multi-room facility capable of performing several concurrent test programs to investigate on a significant engineering scale the safety aspects associated with large liquid metal spills. The facility contains three main test cells shown schematically in Figure 1. The major sodium system can provide up to 2,268 Kg of sodium at initial temperatures of up to 650°C. A smaller portable sodium transfer tank allows the capability of dumping up to 23 Kg of sodium up to 870°C. Auxiliary equipment includes an inert gas flooding system, ventilation fans, an exhaust tunnel, a scrubber-filter building, and a 61 m stack. There are two test chambers for controlled atmosphere tests, and appropriate instrumentation for monitoring temperatures, pressure, and cell atmosphere. Also included is a 100-channel data acquisition system and appropriate recorders.

4.0 DISCUSSION OF LINER SYSTEM TESTS

During a sodium spill, the liner system would be heated very rapidly (and probably non-uniformly) from the cell interior as the sodium spilled into the cell. The rapid heating to very high temperatures would cause rapid thermal expansion of the liner plates producing large compressive stresses in the liners. At the same time, the high temperatures cause the strength of the plate and structure to be reduced. The heated concrete behind the liner plates loses water and, to the extent that water of hydration in the cement is lost, also loses structural strength. The water vapor and other gases given off by the concrete have the potential of producing pressures on the back of liner plates if not adequately vented. The overall result of these complex interactions of heat transfer, increase in stresses, and loss in strength of both plate and concrete could be failure of the liner to retain the sodium or prevent leakage of gases. In order to meet the design objectives (section 1.0)

LARGE SODIUM FIRE FACILITY



HEDL 7612-123.2

FIGURE 1. Large Sodium Fire Facility Schematic.

it is important to have both thorough design analysis and carefully planned tests to verify the analytical predictions and the adequacy of the ultimate designs.

Many small scale tests have been performed to determine effects of sodium concrete reactions, consequences of hydrogen produced by concrete reactions, effects of rapid heating on concrete samples and liner samples, etc. The discussion here will be limited to tests performed by HEDL involving complete liner systems. There are many system design configurations which could be tested, but only two basic wall configurations and one floor configuration have been tested to represent current reactor designs. These configurations are as follows:

Wall configuration A: Edge-welded plates in a cylindrical cell

(see Figure 7)

- Cylindrical cell geometry
- Rectangular plates welded at their edges to structural steel embedded in the concrete
- Steel liner plates nominally against structural concrete
- Venting through pipes which are welded to the liner and pass through the cell interior.

Wall configuration B: Stud-supported plates in a rectangular cell

(see Figure 7)

- Rectangular cell geometry
- Rectangular plates held in place by 1.27 cm diameter by 46 cm long steel studs anchored in structural concrete
- Steel liner plates separated from structural concrete by a 0.63 cm venting gap and 10 cm of lightweight insulating concrete
- Venting through the 0.63 cm gap between the liner plate and insulating concrete to large vent plenums.

Floor configuration: Edge-welded plates and insulating aggregate
(see Figure 7)

- Flat floor
- Rectangular plates welded at their edges to floor beams embedded in concrete
- Steel floor plates separated from structural concrete by 10 cm of gravel for insulation
- Venting through the insulating gravel to large vent plenums.

It is ^{obvious} ~~obvious~~ that many variations and combinations of the design features in these configurations are possible, and future designs will likely incorporate the individual features found to be most advantageous.

In testing cylindrical configurations, such as that shown in Figure 6, both full cylinder tests and cylinder segment tests should be considered. A full cylinder with complete symmetry would be a rather unique and interesting case because each structural embedment would have plate edges pushing from both sides with equal force. On the other hand, an asymmetric configuration would be more realistic because a real cell would have penetrations which would destroy the geometric symmetry, the spill of coolant would likely cause an asymmetric heating of the liner, and buckling of plates around the circumference of the cylinder will not occur simultaneously so that when one plate buckles the adjacent plates and structures are no longer symmetrically loaded. A cylinder which is not fully symmetric in geometry and loading can be evaluated by testing a segment of the cylinder (with adequate edge restraint). Because the asymmetric case appears to be more realistic, and it is more economical to do full scale tests on a segment of a cylindrical cell than on a full cell, tests to date of the cylindrical geometry have been performed using segments of a cylinder rather than a full cylinder.

Of the two liner systems tests, the first test, FT-3, involved only a cylindrical segment of a configuration A wall. The second test, LT-1, incorporated both A and B wall configurations and a floor.

5.0 HIGH TEMPERATURE LINER FEATURE TEST, FT-3

5.1 Test Configuration

The FT-3 test was designed to verify the expected response of an individual liner plate in a configuration A wall to the rapid temperature rise and resultant compressive stresses due to a coolant spill. It was designed to observe directly by both continuous measurement and visual observation the displacements of the liner plate, so liquid metal coolant was not used for heating the plate. High heat flux radiant heaters were used instead. The resulting rate of temperature rise was slower than would be expected in an actual spill of liquid metal coolant, but the rise from room temperature to 593°C in about 45 minutes was rapid enough so that all the expected transient phenomena, with the concrete substantially lagging behind the liner plate in temperature rise, could be observed. Structural steel, structural concrete, and a venting system were provided to complete the liner system and to simulate the actual structural and thermal environment of an actual liner plate. The response of these components of the system to the rapid temperature rise was also determined by the test. Figure 2 illustrates the test configuration and instrumentation.

The FT-3 test configuration consisted of:

- 122 x 122 x 0.63 cm steel (ASTM A-516, Grade 55) liner plate curved to form a segment of a 4.9 m radius cylinder; liner plate welded at its edges to 7.6 cm I-beams embedded in the concrete
- High density concrete with magnetite aggregate and with reinforcing steel
- Very stiff structure around the edge of the test article to provide a high degree of elastic restraint (not rigid)
- Instrumentation:
 - liner potentiometers to measure displacement at five locations
 - thermocouples for temperature measurement at nine locations
 - pressure tap to monitor pressure between plate and concrete

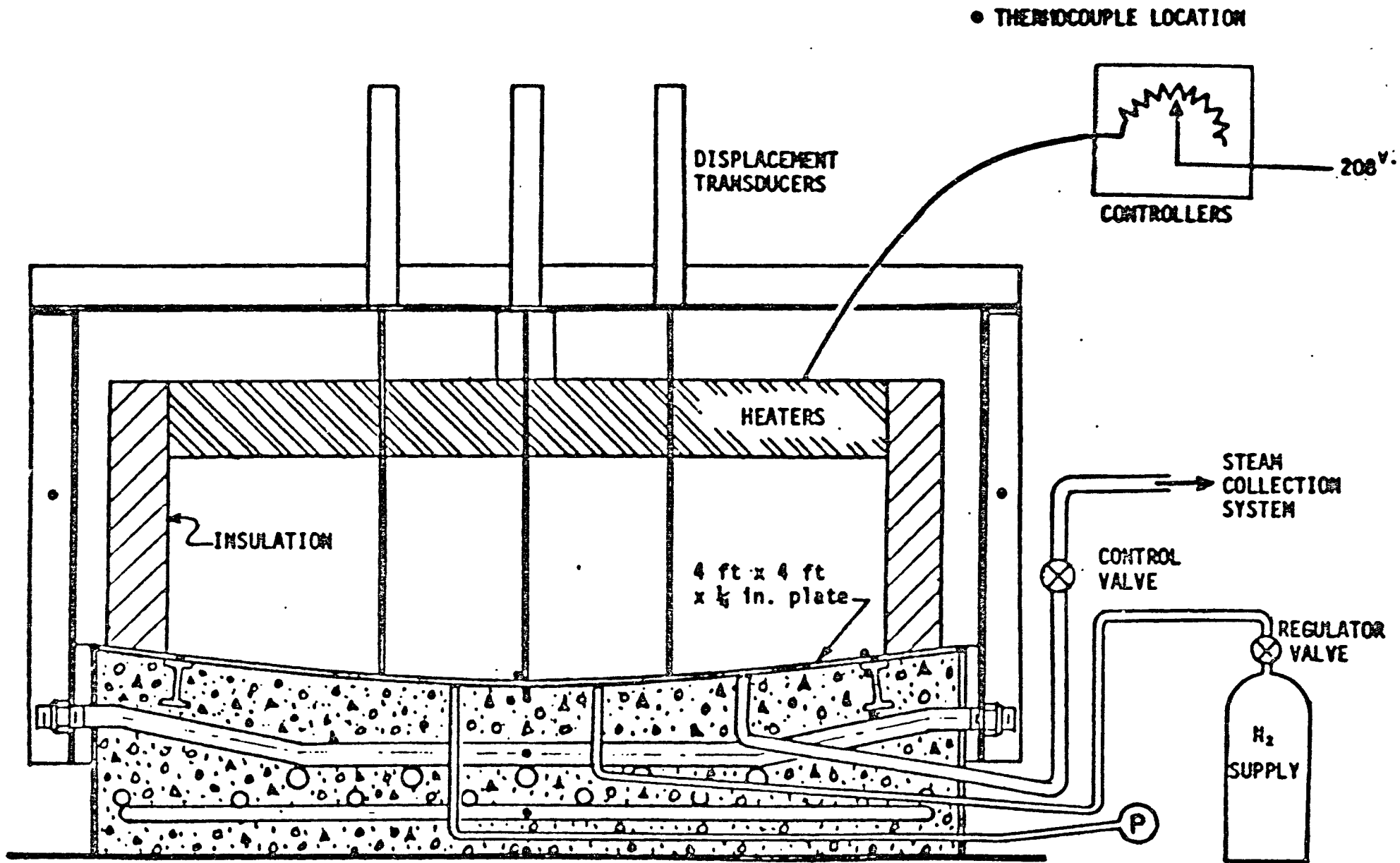


FIGURE 2. FT-3 Test Configuration.

- Heaters:
 - tungsten-filament quartz lamps
 - coiled kanthal resistance heaters
- Pressurization:
 - bottled nitrogen gas.

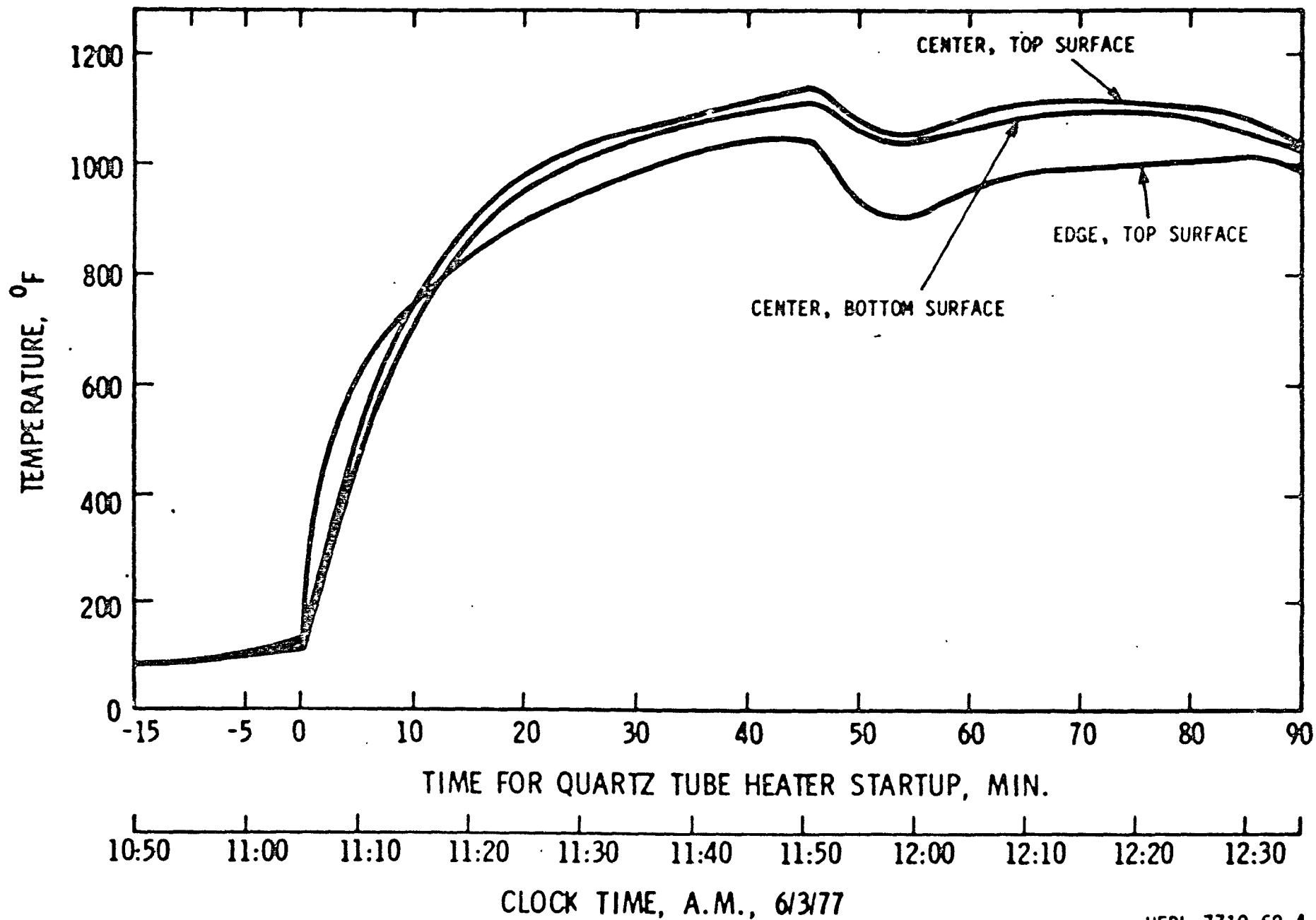
The test objectives were to:

- Determine the response of liner plate to rapid heating to 593°C
- Determine the response of the concrete and supporting structure to rapid heating
- Determine the response of liner plate to pressurization after reaching 593°C.

Pre-test analysis had predicted that the liner plate would buckle due to the compressive stresses and thereby limit the stress to a level which would not cause failure of any sort in the plate or welds. No pre-test analysis of the concrete and embedment structure was attempted.

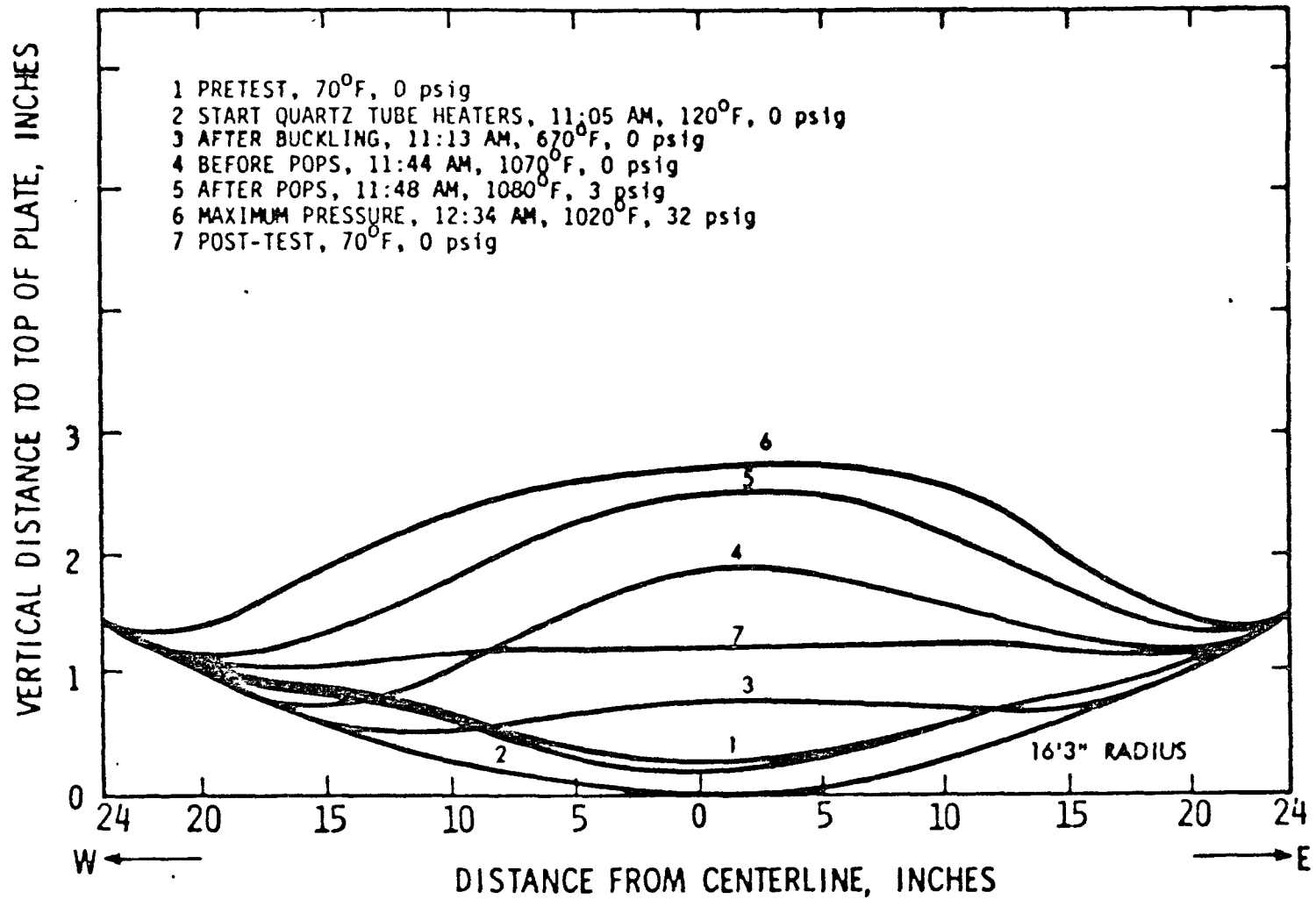
5.2 Test Results

The heating phase of the test was completed successfully. The increase of liner temperature with time is shown in Figure 3. As anticipated, the plate buckled away from the concrete fairly early in the test. This created a gap between the plate and concrete at the center which grew as the temperature increased (see Figure 4). The maximum center deflection reached about 6 cm at 593°C. Compressive stresses in the plate increased as the temperature increased until the plate buckled. After buckling, further expansion just increased the bow in the buckled plate rather than increasing the compressive stresses, since buckling just served to limit the stresses. While at temperature the gap between the concrete and liner was pressurized to 2.2×10^5 Pa (32 psig). No indication of plate or weld failure could be found after the completion of the test and cool-down of the test article. A picture of the buckled liner plate following cooldown is shown in Figure 5.



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FIGURE 3. FT-3 Liner Temperature vs. Time.



HEDL 7710-69.1

FIGURE 4. FT-3 Circumferential Liner Displacement.



FIGURE 5. FT-3 Buckled Liner Plate.

The rapid heating of the liner plate caused fractures in the surface concrete in the vicinity of the embedded structure along with surface spalling. None of the fractures went deeper than the depth of the embedments (i.e. 7.6 cm). Two possible explanations can be advanced to explain the concrete fracturing.

- 1) Thermal cause: rapid non-uniform heating of a constrained concrete surface, especially in the vicinity of embedded metal, is known to cause local spalling and fracturing.
- 2) Mechanical cause: thermal expansion of the liner plate caused it to push outward on the embedded steel structure and on the edge restraint structure. These mechanical forces could have caused great enough movement of the structure to cause local failure of the concrete.

Unfortunately the fracturing of the concrete was not anticipated and so the test instrumentation was inadequate to determine clearly the cause of fracturing. It should be pointed out that the concrete fracturing did not affect the performance of the steel liner, nor was it deep enough to appreciably affect the strength of the concrete structure. It did cause vent paths around the embedments which prevented further pressurization. As a result, the attempt to over-pressurize the liner while holding the temperature at 593°C was unsuccessful.

6.0 LARGE-SCALE LINER SODIUM SPILL TEST, LT-1

6.1 Test Configuration

The LT-1 test was designed to test both wall configurations A and B and the floor configuration (Section 4.0) in a single test with a large-scale spill of liquid sodium (Na) coolant. The test article configuration is shown in Figure 6 and 7. 1588 Kg of sodium at 593°C was spilled through a pipe against the configuration B wall which was initially at room temperature. Then over a period of 2-1/2 days the sodium in the test article was heated to the range of 815°C where it was maintained for 3-1/2 days. The sodium heaters were then turned off and the sodium required about 4 days to cool to 260°C when the sodium was drained. This temperature cycle subjected the walls and floor to the thermal

shock of the spill, plus a rigorous temperature and sodium liquid and vapor environment for a fairly substantial period of time.

The important features of the LT-1 test were

- Two configuration A walls with magnetite concrete:
 - 1) one submerged beneath the spilled sodium coolant with a 61 x 122 x 0.63 cm steel liner plate curved to form a segment of a 4.9 m radius cylinder
 - 2) one above the liquid sodium exposed to the Na vapor with a 65 x 122 x 0.63 cm steel liner plate curved to form a segment of a 5.3 m radius cylinder (and with somewhat different embedment structure)
- 2.1 m high by 1.8 m wide configuration B wall with a 2.1 m high by 0.3 m wide wall for form a configuration B corner; very stiff elastic restraint structure at the edges of the configuration B test section; limestone structural concrete
- Gravel insulated floor with limestone structural concrete
- 1588 Kg of 593°C sodium spilled through a 7.6 cm pipe against the configuration B wall in a period of 1 min 50 sec.; average velocity of the stream impacting the wall was about 12.2 m/sec; centerline of stream was at a 45° angle to the wall.
- Instrumentation:
 - 72 thermocouples throughout the test article including several arrays through the concrete
 - pressure taps on each isolated wall section to verify adequate venting
 - H₂O condensation system on vent lines and sodium vapor above pool
- Three arrays of rod-type heaters:
 - six immersed in the spilled sodium pool
 - one array clamped to the outside of each of the two transition walls.

The test objectives were to:

- Demonstrate the capability of the wall and floor configurations to withstand the thermal shock and harsh thermal environment of a coolant spill and long-term exposure to liquid vapor coolant
- Obtain data on concrete thermal history and water and gas release from large sections of structural concrete
- Determine the effects of the spill on all the components of the liner systems as well as the combined effects on the total liner systems.

Analysis prior to the test had predicted that the wall and floor designs were adequate to withstand the test cycle with no failures. Quantities of water and gas released by the concrete were predicted based on small scale tests on small concrete samples.

6.2 LT-1 Test Results

The spill of sodium into the cold (room temperature) LT-1 test article chilled the sodium to about 338°C during the first 3 hours before the heaters were able to begin to raise the temperature. The cycle was then completed as outlined in Section 6.1. The sodium pool temperature as a function of time is shown in Figure 8. After completion of the test and removal of the sodium and reaction products (from exposure of the sodium residue to air and water), the walls and floor received thorough examination. Visual examination of all liner plate and visual, magnetic particle, and ultrasonic examination of welds showed no indication of failure and very little distortion. The 61 cm by 122 cm liner plate in the configuration A wall submerged in the liquid sodium buckled as expected (but the gap was less than in FT-3 because the plate was half as large). The maximum bulge at the center when the plate buckled was approximately 1.5 cm; the residual bulge after cool-down was about half as much and so was barely apparent. The large configuration B wall and the floor were relatively flat before the test but both showed some waviness distortion after the test, with maximum amplitude of about 0.63 cm. At the spill impact point on the configuration B wall the plate bulged away from the wall 1.3 cm while the liquid was

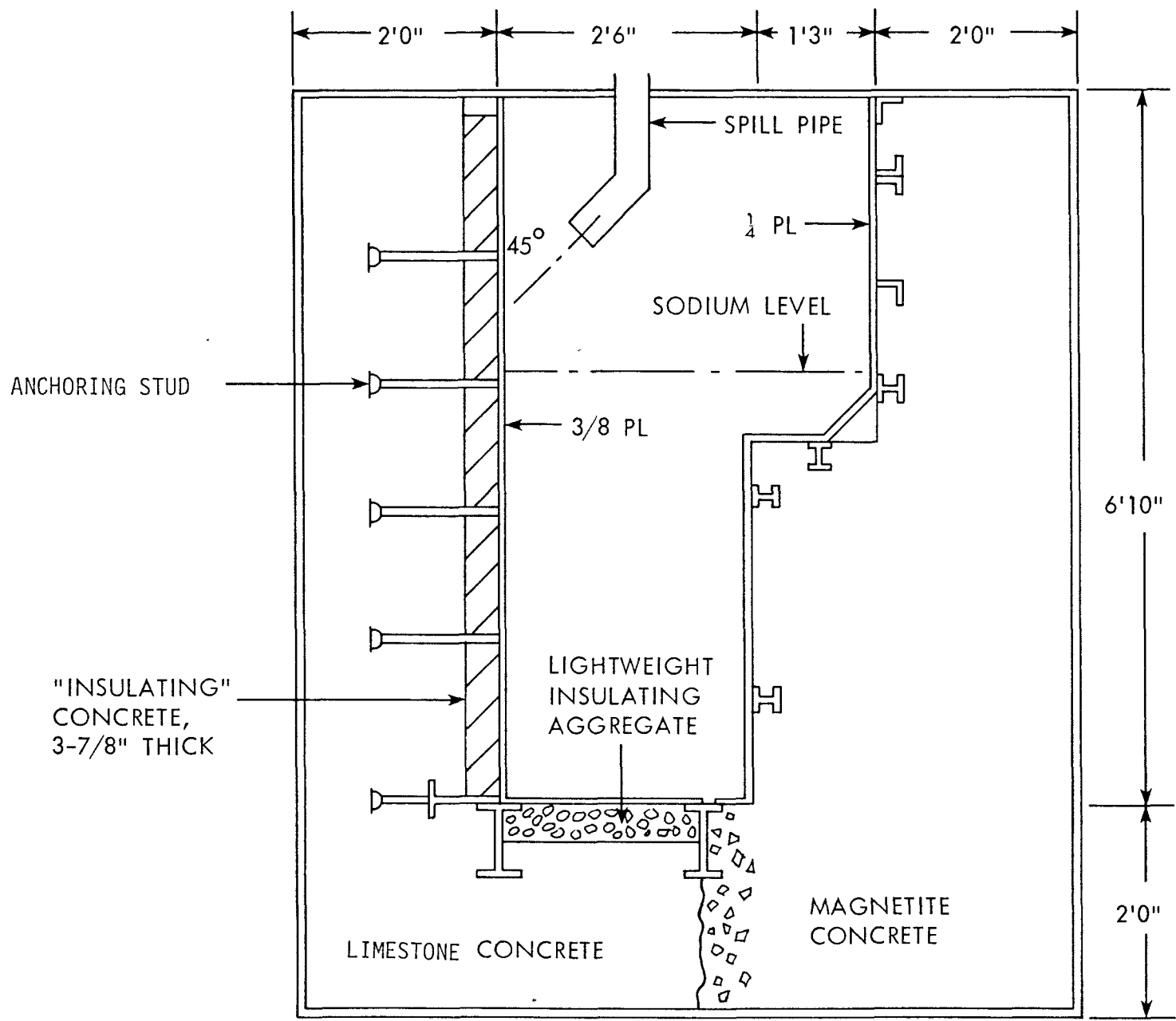
flowing. After the test the bulge had reduced to less than half of the original value and was barely apparent. Close inspection of the spill impact point showed no indication of cracking or other failure initiation.

The pressure behind the liner plates showed no detectable increase throughout the test so the venting was adequate for all concrete surfaces with no indication of plugging having prevented venting. Approximately 1361 Kg of water was collected from the vents, and this constituted about 80% of the total amount used in mixing the concrete. The maximum rate of water release from the limestone concrete based on both the submerged area and surface area above the liquid sodium was 1.94 Kg H₂O/hr per square meter of concrete surface at approximately 40 minutes after the spill. The maximum rate from magnetite concrete was 4.2 Kg H₂O/hr per square meter, approximately 23 minutes after the spill. The limestone concrete released more non-condensable gases than the magnetite concrete. Of the non-condensable gases evolved from both types of concrete, approximately 60 to 80% was CO₂, 20 to 30% was H₂, 5 to 15% was CO, and less than 1% was hydrocarbons.

Both the lightweight insulating concrete and the insulating aggregate in the floor were able to reduce the rate of temperature rise as well as the peak temperature reached in the limestone concrete. Typical concrete temperatures as functions of time are shown in Figures 9, 10, and 11. Taking a distance of 20 cm into the concrete from the liner plate (at about 0.6 m above the floor) as an example, the magnetite concrete in the configuration A wall reached a peak temperature (at the time when the heaters were turned off) of 610°C. The configuration B wall with insulating concrete reached a peak of 575°C at the same distance from the liner; and the floor concrete reached 538°C at that distance. It has not yet been determined whether thermal protection of the limestone concrete had any appreciable effect on strength retention.

7.0 GENERAL CONCLUSIONS

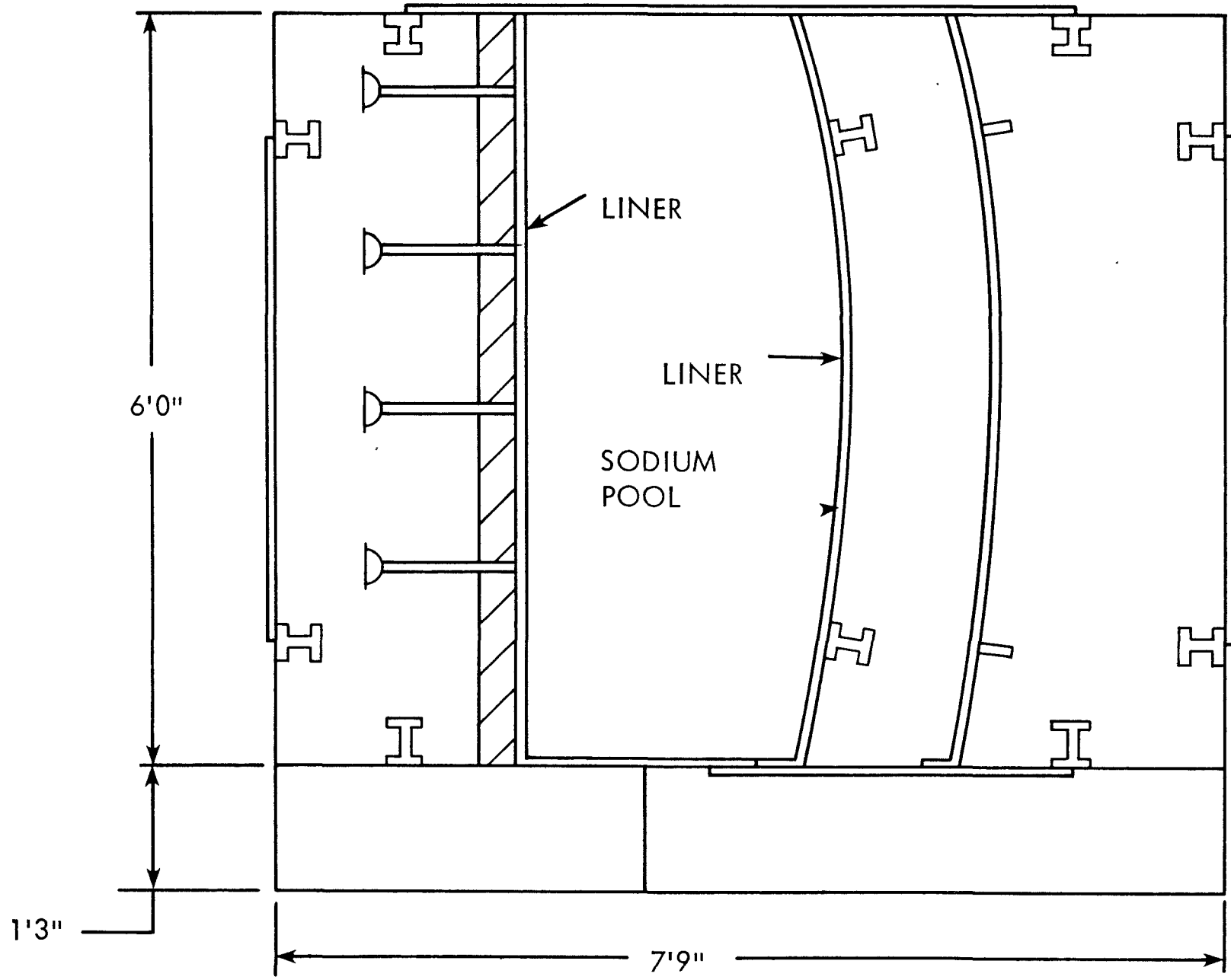
The major conclusion to date is that the liner system designs which have been tested appear entirely adequate to contain coolant spills without sustaining



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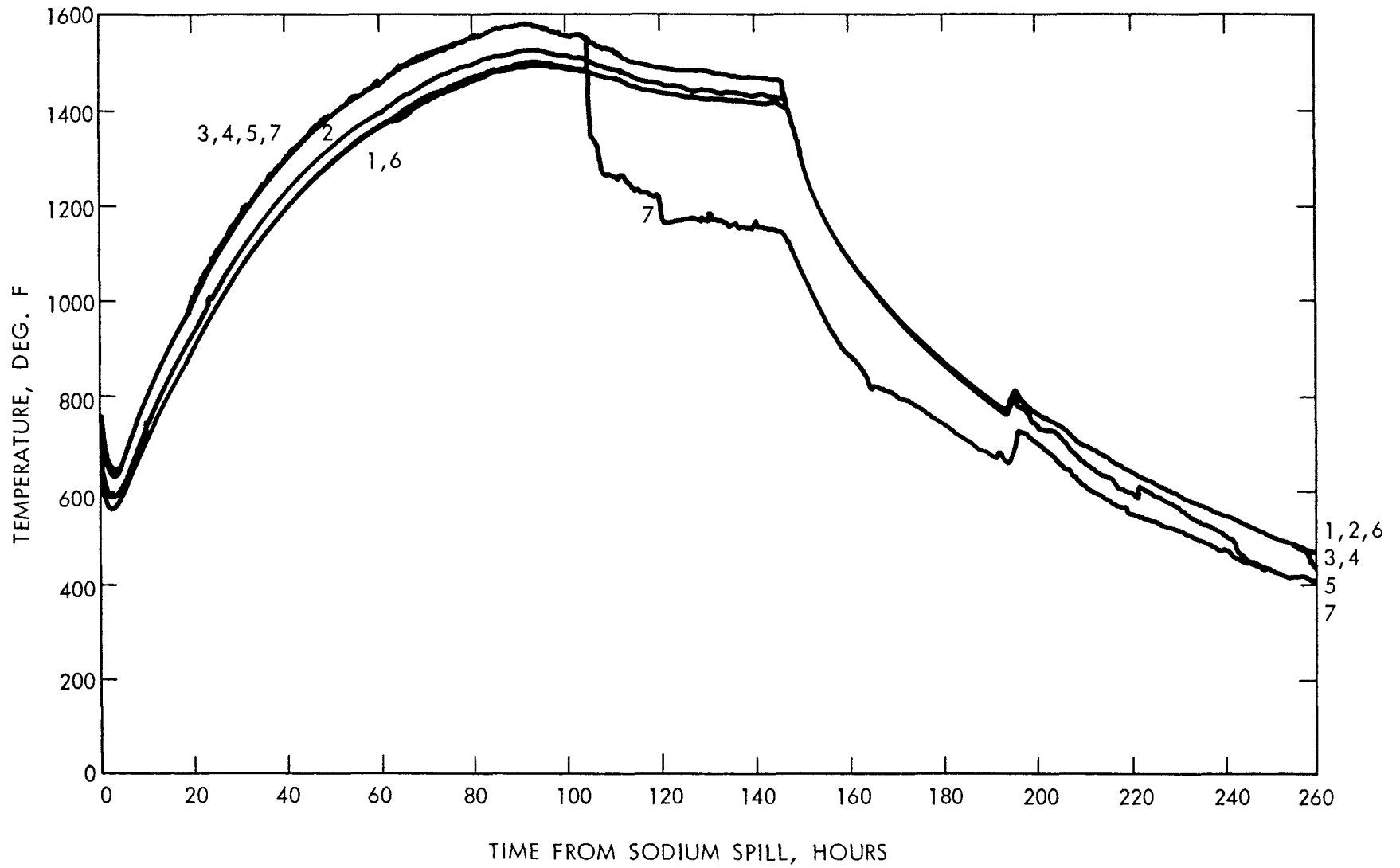
FIGURE 6. LT-1 Test Article Configuration.

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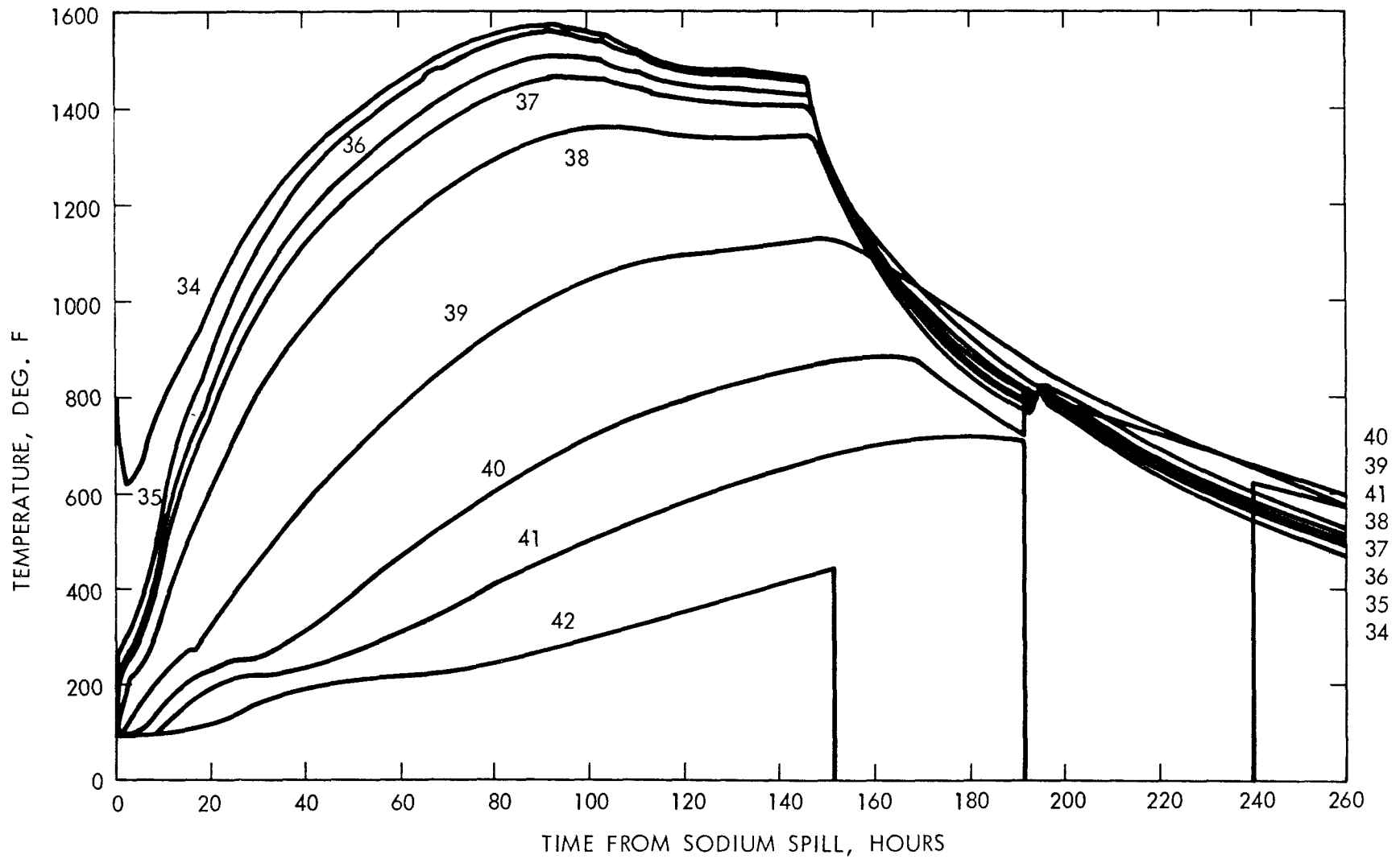
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FIGURE 7. LT-1 Test Article Configuration.



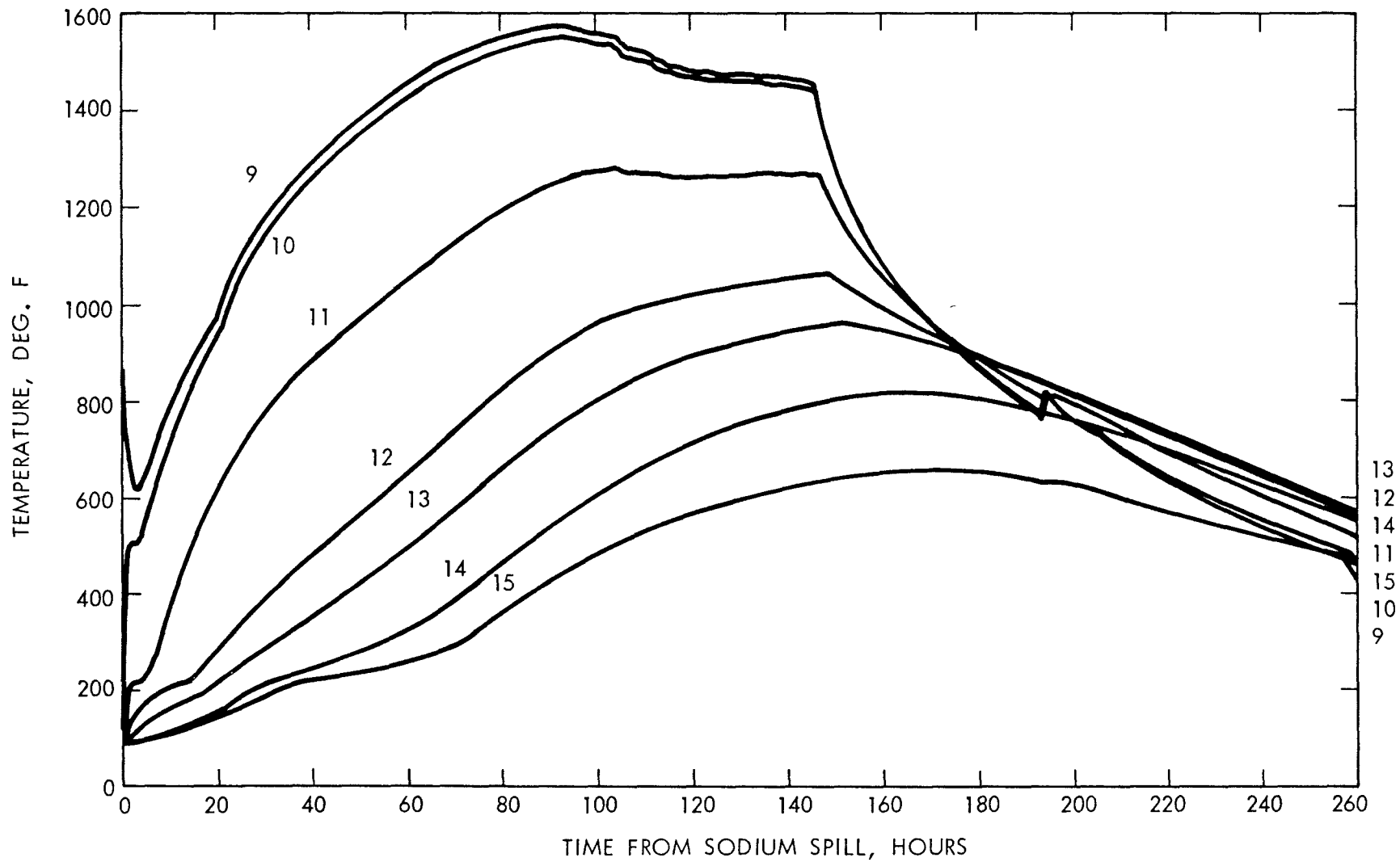
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FIGURE 8. LT-1 Sodium Pool Temperature As a Function of Time.



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FIGURE 9. Concrete Temperatures Behind Configuration A Wall as Functions of Time.



HEDL 7711-129.12

FIGURE 10. Concrete Temperatures Behind Configuration B Wall as Functions of Time.

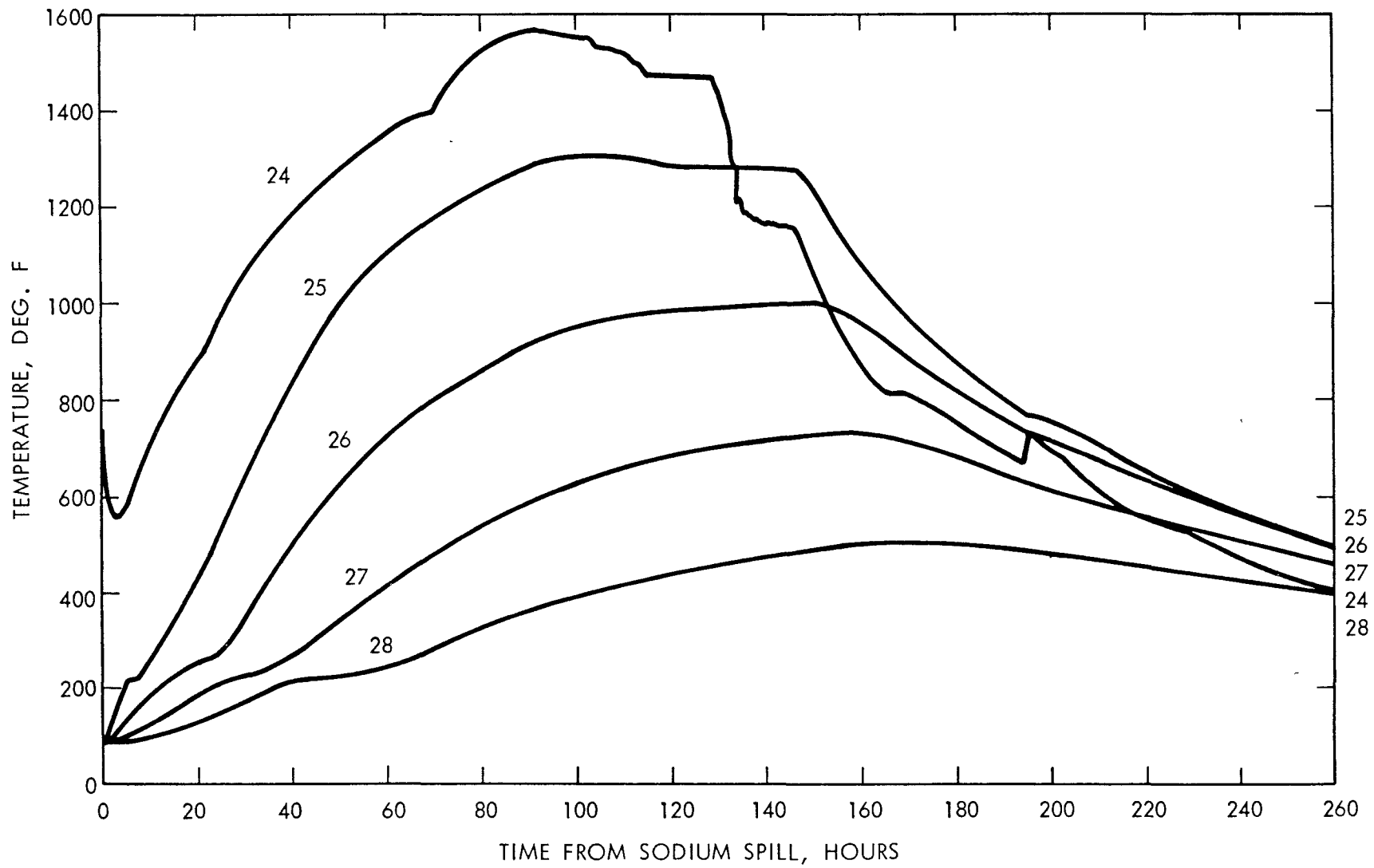


FIGURE 11. Concrete Temperatures Behind Floor Configuration as Functions of Time.

failures which would allow leakage through the liner. The testing experience is limited, and the configurations tested have been constructed with care to avoid defects in the original construction. However, even considering these limitations, the results look very favorable for the designs tested.

Based on the test experience, it appears that current liner designs are conservative because conservative assumptions have been used in the design analysis. The design analysis of such systems require evaluation of the heat diffusion, the resulting thermally-induced stresses, and the deflection of components which is due to both stresses and thermal expansion. All of these phenomena are coupled and the analysis is obviously complex. Often the analysis is made manageable by assuming support structures are fixed and rigid. If the support structure was truly rigid, thermal expansion could only be translated into very high compressive stresses in the steel or concrete held between the rigid supports. It would then be concluded that high stresses could result with possible liner failure. In reality all supporting structure is elastic, regardless of material or construction. The elastic deflection of the support structure partially relieves the liner stresses. Neglecting the elastic deflection of support structures leads to conservative analysis in the strength of the design.

Possible consequences of fracturing of concrete immediately behind the liner are:

- 1) Freeing of the embedments so that the liner is no longer attached to the concrete.
- 2) Altering of the overall strength of the structural concrete wall.
- 3) Interference with venting by concrete rubble.

The tests to date have indicated no adverse consequences from the fracturing of the concrete. Freeing the liner from the wall could be an advantage rather than a disadvantage. The restraint provided where the liner is attached to the concrete is not rigid but it may be rigid enough to prevent buckling of the liner in cases where the distance between supports is small. Freeing the liner

at some of the restraints could promote local buckling which would relieve stresses (and the magnitude of buckling required for stress relief is quite small). None of the fracturing observed to date has penetrated deeper than the depth of the embedments so that effect on overall strength of the wall is probably very small. The concrete rubble which would be broken small enough to enter the opening of a vent would probably be quite porous. Also the fracturing in the tests has lead to creating new vent paths around embedments to adjacent areas, so that the overall effect has been to facilitate venting rather than restrict it. (In the LT-1 test an attempt was made to pressurize one isolated wall area to see the effects of pressurization, but this could not even be done intentionally because of leak paths developed by fracturing.) The preliminary conclusion from tests to date is that no real disadvantage or hazards result from concrete fracturing.