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Holtec Center, 555 Lincoln Drive West, Marlton, NJ 08053
Telephone (856) 797-0900
Fax (856) 797-0909

TOPICAL REPORT ON THE HI-STAR/HI-STORM THERMAL MODEL AND ITS BENCHMARKING WITH FULL-SIZE CASK TEST DATA

Holtec Report No. HI-992252

Holtec Project No. 5014

Report Category: I

Report Class: Safety Related

NON-PROPRIETARY VERSION

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Holtec Center, 555 Lincoln Drive West, Marlton, NJ 08053
Telephone (609) 797- 090
Fax (609) 797 - 090

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Holtec Project No **5014**

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Holtec Center, 555 Lincoln Drive West, Marlton, NJ 08053
Telephone (609) 797- 0900
Fax (609) 797 - 0909

REVIEW AND CERTIFICATION LOG

DOCUMENT NAME :	TOPICAL REPORT ON THE HI-STAR/HI-STORM THERMAL MODEL AND ITS BENCHMARKING WITH FULL-SIZE CASK TEST DATA
HOLTEC DOCUMENT I.D. NUMBER :	992252
HOLTEC PROJECT NUMBER :	5014
CUSTOMER/CLIENT:	GENERIC

REVISION BLOCK

REVISION NUMBER *	AUTHOR & DATE !!	REVIEWER & DATE !!	QA & DATE !!	APPROVED & DATE !	DIST. x
ORIGINAL	Indresh Rampall (IR) 8/12/99	E Rosenbaum 8/13/99	S.S 8/13/99	B.G. 8/13/99	
REVISION 1	Indresh Rampall (IR) 9/29/00	9/29/00	9/29/00	10/6/00	
REVISION 2					
REVISION 3					
REVISION 4					
REVISION 5					
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SUMMARY OF REVISIONS LOG HOLTEC REPORT HI-992522	
Revision 1 Changes: (1) PNNL Benchmark Comparison added. (2) HI-STAR evaluation revised from helium backfill density stipulation to canister backfill pressure (46 psia @70°F). (3) HI-STORM runs @ helium backfill density stipulation deleted and heat load parameterized runs referenced to latest FSAR revision. (4) PNNL HI-STORM evaluation report added as Attachment 1.	
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CHAPTER 1: BACKGROUND AND REPORT OUTLINE

1.0 Background

In absolute terms, the heat dissipation requirements imposed on dry storage casks are quite feeble; in the range of 20 to 40 kilowatts (roughly 70,000 to 140,000 BTU per hour). Generically speaking, however, a cask, particularly one equipped with a multi-purpose canister (MPC), is an intrinsically ineffective heat rejection equipment, making the task of maintaining the spent fuel cladding below a certain limit a most challenging design effort. The underlying reason behind the difficulty in removing heat from casks is the presence of several physical discontinuities between the locations of heat generation and the external surfaces of the cask where the internally generated heat is rejected to the outside environment. In the case of Holtec's HI-STORM system (Docket # 72-1014), illustrated in Figure 1.1, the heat transfer problem is somewhat ameliorated by the fact that the external surface of the MPC is cooled by the sweeping action of the air mass propelled upwards in the annular gap between the MPC and the overpack by the buoyancy effect. In the all-metal, dual-purpose HI-STAR system (Figure 1.2), on the other hand, heat rejection must occur from the external surfaces of the overpack by natural convection and radiation. Figure 1.3 shows a planar cross section of a typical prior-generation cask wherein the locations of "gaps" are illustrated. A sectional isometric view of the prior-generation cask is shown in Figure 1.4. The gaps in early generation cask designs, illustrated in Figure 1.3, are the choke locations that derate the heat transmission capacity of the cask: they have been eliminated, wherever possible, in the Holtec MPCs by utilizing a honeycomb basket design.

In an MPC system, wherein all multi-purpose canisters and overpacks must be interchangeable, their interfacial gaps must be made large enough to account for fabrication tolerances. This further exacerbates the heat rejection problem. The HI-STAR/HI-STORM MPC design seeks to overcome some of the "gap" problem by utilizing an integrally welded honeycomb basket, as opposed to the "box and disk" basket (Figure 1.4) used in some of the older cask (such as the IF300) designs. The MPC-68 basket shown in Figure 1.5 is typical of the HI-STAR/HI-STORM

family of multi-purpose canisters. The cell walls in this basket are continuous and integral, eliminating the box-to-disk gap encountered in the old designs. The remaining gaps, namely those between the fuel and the cell, between the basket and MPC enclosure vessel, and between the MPC and overpack, are *irremovable* for a variety of reasons.

The cell-to-spent nuclear fuel (SNF) gap and MPC-to-overpack gaps cannot be eliminated for obvious reasons. Considerations of thermal stress warrant that the basket be free to expand inside the MPC enclosure vessel, ruling out the possibility of making a welded connection between the two. All MPC system designers must devise means to transport heat from the stored fuel in the presence of irremovable gaps, whose size is subject to some dimensional (fabrication) uncertainty, which contributes to a reduction in the heat rejection capacity of the cask.

The HI-STAR/HI-STORM MPC design attempts to overcome the above-mentioned built-in impediments to heat transfer by exploiting another design opportunity afforded by the honeycomb basket construction (and not available in the "box and disk" basket designs), namely, the provision of a thermosiphon feature. By providing openings at the bottom of the cells and an open plenum at the top, a complete recirculatory path for thermosiphon action is created (the downcomer for the fluid (helium in Holtec's systems) is naturally present in honeycomb designs), as illustrated in Figure 1.6. The thermosiphon feature built into the HI-STAR/HI-STORM MPCs is quite similar to design provisions in recirculating steam generators in PWRs and high-density spent fuel racks for both wet and dry scenarios [7].

By incorporating the convective heat transfer feature, the HI-STAR/HI-STORM Systems summon internal convection to aid in heat transport. Recognizing that the effectiveness of the thermosiphon effect is directly influenced by both the heat capacity and the mass density of the circulating fluid medium, helium was selected as the backfill medium (high heat capacity). Further, the helium initial backfill pressure was set above 2 atmospheres. The bottom holes in the basket (called "mouse holes", and indicated in Figures 1.5 and 1.6) were enlarged to ensure a certain minimum opening size under the worst-case scenario of debris fallout, and the top plenum was sized to provide minimal resistance to fluid circulation. A skeletal model of the HI-

STAR system, with increased visual emphasis on the thermosiphon effect, is shown in Figure 1.7.

Finally, it should be noted that heat transfer through recirculatory fluid flow within the HI-STAR/HI-STORM MPC is a design necessity caused by Holtec's selection of stainless alloy for the fuel basket. Stainless steel has roughly one-third of the conductivity of carbon steel, which is why cask designers have preferred to use carbon steel in fuel baskets to obtain reasonable overall heat transfer capability in the cask systems. Carbon steel, however, has been at the root of several manufacturing and operational problems in the industry (e.g., cracking during forming, rusting, hydrogen generation, etc.). Considerations of environmental compatibility and corrosion resistance led HI-STAR/HI-STORM designers to abjure carbon steel in favor of stainless steel in MPCs. While the selection of stainless steel for the MPC and its internals has solved the metallurgical and water chemistry issues in the HI-STAR/HI-STORM systems, it derated the system's thermal performance to quite low values (approximately 19 kW and 21 kW for HI-STAR 100 and HI-STORM 100, respectively). Exploiting the buoyancy-driven heat transfer (thermosiphon) in the MPC is the only viable means to lift the thermal performance of an all-stainless basket to respectable levels (approximately 30 kW).

To analyze the HI-STAR/HI-STORM thermal problem, a solution procedure implemented on the commercially available computer code FLUENT [6] incorporates the contributions of the conduction, convection and radiation modes of heat transfer consistent with the Holtec MPC design. This model and its ventilated counterpart were utilized in the HI-STAR [2] and HI-STORM [3] licensing reports, respectively, without recognition of the thermosiphon effect. The object of the benchmarking effort documented in Chapter 2 of this topical report is to demonstrate that the FLUENT thermal model, with due recognition of the thermosiphon effect, conservatively simulates third-party test data with reasonable accuracy.

In Chapter 2 of this report, the extensive code benchmarking program undertaken by Holtec is described in detail. Chapter 2 also seeks to acquaint the reader with the actions taken to ensure that the analysis methodology and the computer code utilized in the subsequent evaluations are

robust and appropriate. The key feature of this chapter is the comparison of Holtec's computer programs and modeling methods with independent, high-quality experimental cask thermal performance data.

Having established the effectiveness of Holtec's computer programs and modeling methods in Chapter 2, the thermosiphon-enabled thermal performance of Holtec's HI-STAR and HI-STORM dry cask systems is analyzed in Chapters 3 and 4, respectively. In each of these two chapters, the modifications in the previously NRC-accepted HI-STAR and HI-STORM thermal models to enable the thermosiphon mechanism are described. Thermal performance results for the two systems, obtained using the thermosiphon-enabled thermal models, are also presented.

This topical report is a successor document to three previous Holtec topical reports submitted to the SFPO of the USNRC. These previously submitted reports are:

i. HI-971619, "Benchmarking the HI-STAR/HI-STORM Thermal Model with TN-24P Test Data" (April 1997)

ii. HI-971722, "A Revised Thermal Model with Parametric Study of Key Variables" (June 1997)

iii. HI-971741, "Benchmarking of the Revised Thermal Model with TN-24P Test Data" (August 1997)

The above-mentioned topical reports were reviewed by the Commission in the course of the SFPO's evaluation of the HI-STAR storage and transport SAR submittals. However, changes to the thermal model arising from the HI-STAR/HI-STORM certification process required that the benchmarking of the "final" (SER-consistent) MPC thermal model be reperformed. Accordingly, this topical report contains a complete description of the benchmarking of Holtec's final thermal model (for HI-STAR and HI-STORM Systems) against full-size cask (TN-24P) test data collected by third parties. The extensive benchmarking of the thermal model with due recognition of internal convection (thermosiphon) establishes its technical veracity, and enables

its use to predict the thermal performance of HI-STAR 100 and HI-STORM 100 Systems with confidence.

Early this year (ca. 2000), PNNL performed an in-depth thermal characterization of the HI-STORM 100 System using the computer code COBRA-SFS. COBRA-SFS, like FLUENT, is a well-recognized fluid dynamic code with an extensive history of applications in the nuclear industry. The results for PNNL's analyses provide an independent basis to benchmark the Holtec HI-STORM 100 thermal model. The comparison with PNNL COBRA outputs, as we describe in this report, show that the HI-STORM 100 model results are consistently and uniformly conservative by a modest margin.

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FIGURE 1.1
AIR COOLING OF THE MULTI-PURPOSE CANISTER IN THE HI-STORM SYSTEM

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FIGURE 1.2
HEAT REJECTION IN THE HI-STAR 100 SYSTEM

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FIGURE 1.3
LOCATION OF HIGH THERMAL RESISTANCE REGION IN A CASK

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FIGURE 1.4
TYPICAL FUEL BASKET DESIGN WITH BOXES AND DISKS
(NOT USED IN HI-STAR/HI-STORM MPCs)

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FIGURE 1.5
ISOMETRIC VIEW OF THE MPC-68 BASKET

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FIGURE 1.6
THERMOSIPHON ACTION IN THE MPC-68 CANISTER

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FIGURE 1.7
MPC INTERNAL HELIUM THERMOSIPHON FLOW MODEL
FOR HI-STAR 100 SYSTEM

CHAPTER 2: BENCHMARKING THE HI-STAR/HI-STORM THERMAL MODEL

2.1 Background

As stated in Chapter 1, the object of the benchmarking program is to establish the veracity of the FLUENT Computational Fluid Dynamics (CFD) code [6], and the solution procedure utilized to develop thermal models to predict the temperature fields within the HI-STAR/HI-STORM MPCs. The benchmarking effort essentially consisted of simulating the multi-year experiments carried out by an industry group on a full-scale cask. The organizations participating in the cask experimentation project were the Electric Power Research Institute (EPRI), the Virginia Power Company (VPC), the Idaho National Engineering Laboratory (INEL), and the Pacific Northwest Laboratory (PNL). A prototype vertical cask containing a 24-cell basket, known as TN-24P, was used for the testing. PWR spent fuel assemblies (Westinghouse 15x15) discharged from VPC's Surry reactor were loaded in the cask to generate decay heat. A complete and comprehensive account of the tests, test results, and computer simulation of the tests is contained in a PNL prepared report published by EPRI [1]. In its report, the Electric Power Research Institute endorsed the PNL/VPC data "to evaluate other heat transfer codes" [1, p. 2-5].

The EPRI/INEL/VPC/PNL cask tests, hereinafter referred to as the TN-24P tests, are most germane to the thermal model utilized in the thermal-hydraulic analysis of the MPCs. Figures 2.1 and 2.2, respectively, show the vertical and horizontal cross sectional views of the TN-24P. The elevation cross section (Figure 2.1) clearly shows the top and bottom plenums in the TN-24P. The downcomer (the vertical passage around the periphery of the basket for downward flow of the gas from the top plenum to the bottom plenum) is clearly identified in the horizontal cross section (shown shaded in Figure 2.2).

From the thermal-hydraulic standpoint, Holtec's MPC designs and theTN-24P are quite similar. The hydraulic diameters of the MPC-24 and MPC-68 downcomer are 5.08 inches and 3.63 inches, respectively, while that of the TN-24P is 5.20 inches. The downcomer in the MPC-68 is

shown in Figure 2.3 to enable a visual comparison with the TN-24P (Figure 2.2). Another desirable aspect of the TN-24P tests is the appreciable decay heat (20.6kW) used in testing. The fuel assemblies were extensively instrumented to yield reliable temperature data. The fuel assemblies were installed in the storage cavities in such a manner that the heat generation approximated radial axisymmetry.

Of course, there are certain differences between the TN-24P and Holtec's dry storage systems, which must be recognized in the benchmarking analysis work and in interpreting the results. These are:

a. The top and bottom plenums in the TN-24P are much smaller than those in the HI-STAR/HI-STORM MPCs. This may have inhibited thermosiphon circulation in the TN-24P and made the modeling accuracy of the top and bottom plenums more important (in the data correlation effort). The relatively large top and bottom plenums in the HI-STAR/HI-STORM MPCs render them somewhat unimportant barriers to gas flow.

b. The TN-24P basket, constructed in the manner of the honeycomb (like Holtec's MPCs), featured an all-aluminum basket in contrast to high-alloy stainless steels used in the Holtec MPCs.

c. The TN-24P tests were run at relatively low-test condition gas pressures (~22 psia) that rendered the mass density of helium too low to fully manifest the thermosiphon effect in the helium tests. The nitrogen tests, however, owing to the higher molecular weight of nitrogen, were an effective witness to the internal convective circulation in the cask.

d. The TN-24P did not feature an MPC enclosure. Therefore, an MPC-to-overpack gap did not need to be modeled in the benchmark simulations.

The TN-24P tests were carried out under six discrete scenarios. Tests were run in vertical and horizontal configurations with three conditions of internal environment: lightly pressurized helium (~22 psia), lightly pressurized nitrogen (~22 psia), and nominal vacuum. The extensive body of temperature data gathered from these tests was correlated by PNL with the predictions of the computer code COBRA-SFS [1]. Holtec's benchmarking effort has been focused on determining how the predictions of the HI-STAR/HI-STORM thermal model compared with the

test data. For this purpose, except for enabling of the thermosiphon effect, a thermal model for the TN-24P was prepared using the same approach as the models prepared for the HI-STAR/HI-STORM MPCs documented in the HI-STAR and HI-STORM TSARs. Specifically, the thermal model has the following features:

a. The equivalent conductivity of the fuel assembly situated in the storage cell is computed using a finite-volume procedure.

b. The basket/fuel assemblage is simulated as an axisymmetric continuum with an equivalent radial thermal conductivity.

c. The hydraulic resistance of the fuel in the axial direction is modeled using a porous medium of equivalent permeability and inertial resistance.

d. The hydraulic resistance in the downcomer is quantified by an equivalent hydraulic diameter.

e. The gap between the basket and the enclosure vessel is explicitly modeled as a gas-filled region (lightly pressurized helium or nitrogen, as appropriate), or as an ultra-low pressure gas with essentially nil thermal conductivity for vacuum condition.

The balance of this chapter provides a systematic description of the benchmarking of FLUENT and Holtec's FLUENT modeling approach for the HI-STAR and HI-STORM Systems. It is important to recognize that the benchmarking effort using the TN-24P data does not merely benchmark the code; it also benchmarks the manner in which FLUENT is implemented to solve the HI-STAR/HI-STORM thermal problem. Qualification of FLUENT by benchmarking against other physical problems by others is summarized in Appendix A.

2.2 Relevance and Synoptic Description of TN-24P Test Data

The TN-24P cask is illustrated in Figure 2.4. The preceding discussion sets forth the technical relevance of the TN-24P tests to the HI-STAR/HI-STORM thermal analyses. The key items of pertinence of the TN-24P tests may be summarized in four points, namely:

a. Independent test data from an extensively instrumented full-scale cask recorded and summarized in an EPRI report (NP-5128, April 1987) ensuring the objectivity of the experimental work.

b. Test data gathered under lightly pressurized helium, nitrogen, and evacuated conditions permit discerning of thermosiphon (vertical) and conduction/radiation-only (horizontal) conditions.

c. Horizontal and vertical orientations tested under two different gas environments, thus providing a quantitative assessment of gas density and heat capacity effects.

d. Reasonably high heat load (20.6 kW) provided by real life fuel assemblies (24 Westinghouse 15x15 spent fuel assemblies from Surry).

The EPRI report contains test data for six discrete runs. We identify them as follows:

Case No.	Definition
1	Cask vertical, vacuum (2.4 mbar)
2	Cask horizontal, vacuum (1.1 mbar)
3	Cask horizontal, nitrogen gas (1580.5 mbar)
4	Cask horizontal, helium gas (1525.1 mbar)
5	Cask vertical, nitrogen gas (1529.4 mbar)
6	Cask vertical, helium (1506 mbar)

The TN-24P test results constitute a large body of data that we will present in conjunction with the results from a thermal model of the TN-24P prepared in the manner of the HI-STAR/HI-STORM thermal model. However, some summary observations from the test data can be elicited without comparison:

a. Evidence of internal convection in vertically oriented nitrogen and helium runs is unmistakable.

b. Considerable upward axial temperature skew in vertical nitrogen runs is found. Helium runs show a relatively smaller upward shift of the peak of the temperature curve.

c. Significant reduction in the peak cladding temperature is observed in the vertical nitrogen run when compared to the horizontal run.

In summary, the TN-24P test results establish the thermosiphon mechanism as a credible and significant means to dissipate heat in the interior of a basket designed for this purpose.

2.3 Numerical Simulation of TN-24P Tests

Before explaining the development of the TN-24P thermal simulation, it is helpful to revisit the process described in refs. [2,3] to create a HI-STAR/HI-STORM thermal model. The procedural steps involved in creating Holtec's thermal model, explained in detail in references [2] and [3], can be summarized as follows:

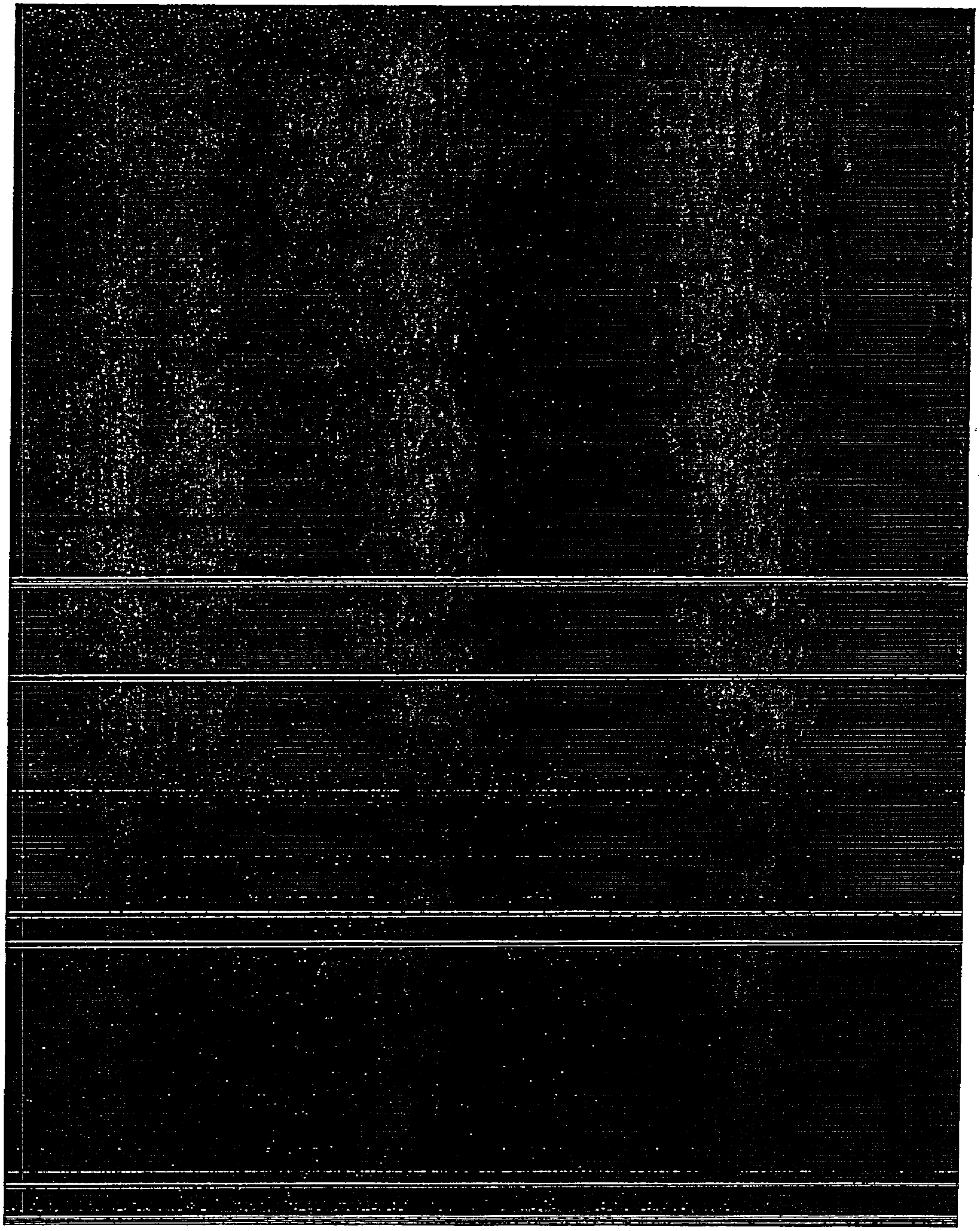
a. In the first step, the SNF/basket assemblage is modeled on ANSYS [8] to determine the equivalent in-plane thermal conductivity of the basket/fuel region that is replaced by a continuum.

b. The resistance to vertical flow in the cell (SNF interstitial space) is computed for the given spent fuel geometry in terms of an equivalent permeability and inertial resistance of a porous medium.

c. The contained helium in the porous continuum, along with the enclosure vessel (i.e., the top and bottom plenums and the downcomer), is modeled on the CFD code FLUENT [6] with sufficient discretization to provide a detailed articulation of the temperature field.

d. The heat generation within the fuel assemblies is applied in the porous medium with an axial profile appropriate for the fuel assemblies.

A detailed overview of the HI-STAR thermal model, from which the TN-24P model is directly adapted, is presented in Chapter 3. For more complete descriptions, the reader is referred to the HI-STAR [2] or HI-STORM [3] reports.



2.4 Input Data

Thermophysical properties of helium and nitrogen fill gases obtained from Rohsenow and Hartnett (ref. [4]) are summarized in Tables 2.1 and 2.2. The TN-24P cask geometry data extracted from the EPRI report is presented in Table 2.3. A summary of key TN-24P material properties is presented in Table 2.4. Experimental measured temperature and pressure data for the TN-24P cask were obtained from Appendix C of the EPRI report [1]. Based on the thermophysical and cask geometry data, an ANSYS finite-element based model of the TN-24P basket cross-section is developed in a manner which is identical to the modeling methodology developed for the HI-STAR/HI-STORM Systems (see Section 4.4.1.1.4 of the HI-STAR TSAR [2]). A cross-sectional view of the TN-24P basket finite element model (1/8 symmetry) is shown in Figure 2.5. In this figure, the honeycomb structure with the square openings represents the TN-24P aluminum basket structure. The fuel assemblies that reside in each of the 24 basket openings are replaced by an equivalent homogeneous region with an effective W-15x15 fuel assembly in-plane conductivity. The effective conductivity evaluation includes heat dissipation by conduction through the gaseous medium filling the open spaces and radiant energy exchange within the array of fuel rods. The fuel assembly effective conductivity determination uses the modeling methodology developed for the HI-STAR/HI-STORM Systems (see Section 4.4.1.1.2 of the HI-STAR TSAR [2]). In Tables 2.5 and 2.6, the effective fuel assembly and basket conductivity results as a function of temperature and fill gas are presented.

With the inclusion of internal circulatory motion of gas in the TN-24P and HI-STAR/HI-STORM thermal models developed in the present study, it is recognized that convective heat dissipation in the downcomer region will occur. To appropriately model convective heat transfer in the downcomer region, the basket-to-cask annulus region is assigned the conductivity properties of the fill gas. This is a conservative assumption because the gap between the basket and the cask inner wall modeled as an equivalent hydraulic annulus overstates the conduction gap and thus penalizes conduction heat transfer.

2.5 Comparison of Holtec's Thermal Model Results with TN-24P Test Data

In Figure 2.6, the various axial TN-24P basket thermocouple probe locations are labeled for identification purposes. Most of the discussion of results in this section pertains to the D1 probe in the hottest (i.e., most heat emissive) fuel assembly measured test data.

The peak temperature results from the thermal model, the subject of this benchmark effort, are provided in Table 2.7. The following conclusions with respect to the thermal model are immediately deduced from Table 2.7.

a. The numerical solution is conservative in comparison to the measured peak data; the margin varies from 10 to 44°C.

b. The margin for the case of the horizontal runs is greater than that in the vertical runs. This is to be expected because, in actual tests, physical contact is established in the horizontal test cases that increase heat transfer and reduces the peak temperatures. The FLUENT solution, fettered by the assumption of axisymmetry, cannot simulate this physical contact and therefore contains an additional conservatism with respect to the horizontal runs.

In the following, a concise discussion of the results for each of the six benchmark cases is presented.

Cases 1 and 2: Vacuum Runs

Figure 2.7 shows the computed basket centerline temperature along with the test data from the vertical and horizontal vacuum runs. Clearly, the results are conservatively biased. Insofar as the vacuum runs do not involve any fluid environments, these cases confirm the conservatism in the conduction and radiation elements of the thermal model.

Case 3: Horizontal Nitrogen Run

As shown in Figure 2.8, the numerical solution uniformly bounds the test data. Since the horizontal case does not involve any thermosiphon effects, these benchmark results reaffirm the conservatism of the conduction and radiation elements of the model. The relatively large conservatism displayed by the numerical solution in this case is due to the metal-to-metal contact in the test, which the FLUENT solution does not incorporate.

Case 4: Horizontal, Helium Run

Figure 2.9 is the helium counterpart of Figure 2.8. Once again, the centerline axial temperature tracks the test data with a conservative bias. Like Case 3, this benchmark imputes confidence in the conservatism of the thermal model in the absence of internal convection.

Case 5: Vertical, Nitrogen Run

Figure 2.10 provides the axial temperature plots. The axial upward shift of the peak temperature in the test runs, evidence of thermosiphon action, is also predicted by the numerical solution. Indeed the axial upward drift in the case of test data is even more pronounced than the numerical results. The good qualitative agreement with test results confirms that the thermosiphon features of the model are captured by the thermal model. The conservative bias, observed in the results confirms the suitability of the model for providing a method to bracket the thermal characteristics of casks from above.

Case 6: Vertical, Helium Run

Figure 2.11 shows the centerline axial temperature results. The low density of helium at low operating pressure is found to diminish the thermosiphon action in both the test data and the numerical simulation results. A substantial conservative trend in the numerical results is observed.

Cases 5 and 6 attest to the veracity of the internal convection aspects of the FLUENT model.

Temperature contour plots for the vacuum, helium, and nitrogen runs are depicted in Figures 2.12 through 2.16.

The above temperature plots show that the FLUENT thermal model consistently predicts higher peak cladding temperatures than the experimental data for both vertical and horizontal orientation scenarios. This result is consistent with our objective to qualify a thermal model that provides a reasonable level of conservatism in the predicted solution. In other words, the FLUENT thermal model has been deliberately rendered conservative through modeling assumptions such that the predicted temperatures uniformly envelop the temperatures that would be achieved in real life. These modeling assumptions are described in Chapter 4, Section 4.4.6 of the HI-STAR TSAR. To fix ideas, we summarize some key assumptions below.

a. The axial thermal conductivity of the basket/SNF assemblage is set equal to its planar conductivity. This assumption penalizes the axial heat transfer in the fuel basket because the in-plane conductivity of the assemblage, reduced by the presence of helium gaps, is much lower than its axial value.

b. The axial flow resistance of the homogenized basket space is overestimated by employing theoretical bounding hydraulic loss coefficients.

The above assumptions have a direct effect on the rate of helium recirculation, thus producing an enveloping cladding temperature profile.

In the horizontal configuration, the principal source of conservatism lies in the axisymmetry assumption in the FLUENT model that implies that the basket and cask centerlines are co-linear and that there is a uniform radially symmetric gap between them. In reality, the basket is in metal-to-metal contact with the cask in the horizontal configuration, leading to flow of heat that is unrecognized in the FLUENT model.

In conclusion, the benchmarking effort proves that the FLUENT solution is uniformly conservative for both vertical and horizontal storage configurations. Therefore, this model can be utilized with full confidence to predict the thermal performance of the HI-STAR cask that is the subject of our presentation in the next chapter.

Table 2.1 THERMOPHYSICAL PROPERTIES OF HELIUM			
Heat Capacity Data $C_p = 1.24$ Btu /lbm/°F			
Gas Thermal Conductivity Data			
T (EK)	366.7	505.5	644.4
k (Btu/ft-hr-EF)	0.0976	0.1289	0.1575
Gas Viscosity Data			
T (EK)	366.5	512.4	665.0
Φ(ΦP)	220.5	288.7	338.8

Table 2.2			
THERMOPHYSICAL PROPERTIES OF NITROGEN			
Heat Capacity Data			
T (EK)	300	500	700
C_p (cal/g-EC)	0.249	0.252	0.262
Gas Viscosity Data			
T (EK)	293.7	444.4	745.0
Φ (ΦP)	177.1	239.3	338.1
Thermal Conductivity Data			
T (EK)	300	500	700
k (Btu/ft-hr-EF)	0.0147	0.0235	0.0293

Table 2.3

TN-24P CASK GEOMETRY DATA[H]

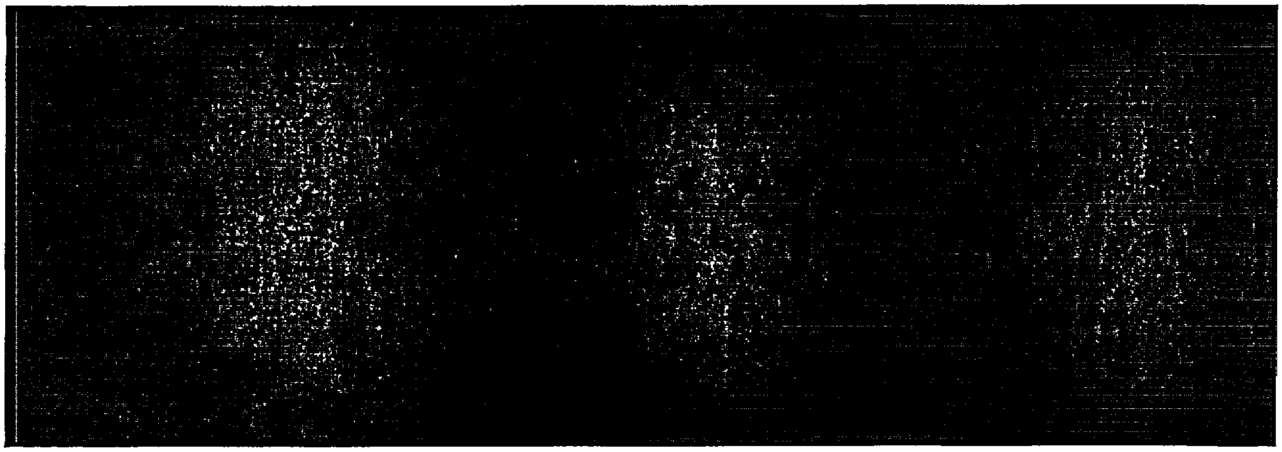
O.D. =	89.8"
Length =	199.2"
Steel shell thickness =	10.6"
Bottom plate thickness =	11.0"
Lid thickness =	11.2"
Neutron shield thickness =	4.2"
Cavity height =	163.4"
Cavity diameter =	57.3"
Basket bottom plenum gap =	1.8"
Basket top plenum gap =	1.1" (cold gap)*
Basket wall thickness =	0.4"

H Data obtained from EPRI report [1].

* The hot gap resulting from axial growth of aluminum basket is much smaller (~1/2 inch).

Table 2.4 TN-24P CASK MATERIAL PROPERTY DATA[H]	
Thermal conductivities:	
Carbon Steel =	24 Btu/ft-hr-EF
Aluminum Basket =	119 Btu/ft-hr-EF
Emissivities:	
Fuel Rods =	0.8
Cask Surfaces =	0.9
Fuel Basket =	0.8
Ambient Temperature =	20EC (68EF)

[H] From [1].



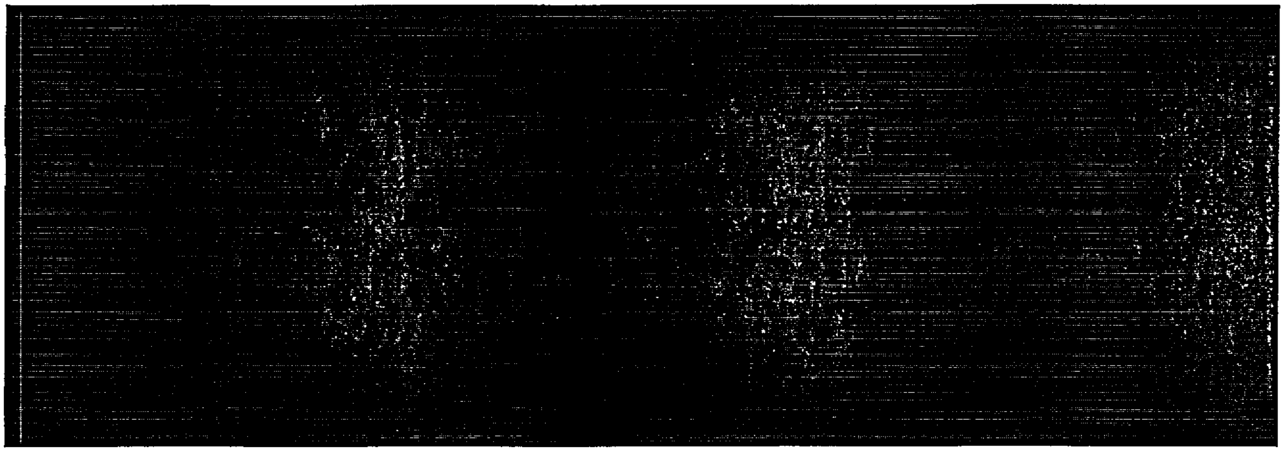


Table 2.7

COMPARISON OF TN-24P PEAK MEASURED AND REVISED MODEL PREDICTED TEMPERATURES

Case	Orientation	Backfill	Measured Guide Tube Temperature (EC)	Predicted Temperature (EC)	Margin* (EC)
1	Vertical	Vacuum	278	292	14
2	Horizontal	Vacuum	268	292	24
3	Horizontal	Nitrogen	247	281	34
4	Horizontal	Helium	208	252	44
5	Vertical	Nitrogen	232	242	10
6	Vertical	Helium	214	240	26

* Margin is defined as the predicted temperature minus the measured temperature. A positive margin means that the FLUENT model conservatively predicts the temperature.

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FIGURE 2.1
VERTICAL CROSS-SECTIONAL VIEW OF THE TN-24P CASK

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FIGURE 2.2
HORIZONTAL CROSS-SECTIONAL VIEW OF THE TN-24P CASK

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FIGURE 2.3
CROSS-SECTIONAL VIEW OF THE MPC-68 BASKET WITH DOWNCOMERS (SHOWN SHADED)

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FIGURE 2.4
TN-24P PWR SPENT FUEL STORAGE CASK

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FIGURE 2.5
TN-24P PLANAR THERMAL CONDUCTIVITY ANSYS MODEL – ELEMENT PLOT

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FIGURE 2.6
TN-24P BASKET AXIAL THERMOCOUPLE PROBE IDENTIFICATION LABELS

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FIGURE 2.7
VACUUM CONDITION THERMAL MODEL TEMPERATURE RESULTS
COMPARISON WITH MEASURED TN-24P DATA

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FIGURE 2.8
HORIZONTAL NITROGEN THERMAL MODEL TEMPERATURE RESULTS
COMPARISON WITH MEASURED TN-24P DATA

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FIGURE 2.9
HORIZONTAL HELIUM THERMAL MODEL TEMPERATURE RESULTS
COMPARISON WITH MEASURED TN-24P DATA

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FIGURE 2.10
VERTICAL NITROGEN THERMAL MODEL TEMPERATURE RESULTS
COMPARISON WITH MEASURED TN-24P DATA

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FIGURE 2.11
VERTICAL HELIUM THERMAL MODEL TEMPERATURE RESULTS
COMPARISON WITH MEASURED TN-24P DATA

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FIGURE 2.12
VACUUM CONDITION TEMPERATURE CONTOURS PLOT
(Temperature in °K units)

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FIGURE 2.13
HORIZONTAL NITOGEN TEMPERATURE CONTOURS PLOT

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FIGURE 2.14
HORIZONTAL HELIUM TEMPERATURE CONTOURS PLOT
(Temperature in °K units)

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FIGURE 2.15
VERTICAL NITROGEN TEMPERATURE CONTOURS PLOT
(Temperature in °K units)

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FIGURE 2.16
VERTICAL HELIUM TEMPERATURE CONTOURS PLOT
(Temperature in °K units)

CHAPTER 3: HI-STAR 100 SYSTEM THERMOSIPHON-ENABLED THERMAL PERFORMANCE FOR STORAGE

3.0 Introduction

The HI-STAR 100 System [2] is designed for long-term storage of spent nuclear fuel (SNF) in a vertical position. The HI-STAR internal basket design in combination with decay heat dissipation and gravity create conditions for the onset of fluid motion in the open internal cavity spaces. In a vertical orientation, the gravity acts to produce circulation of fluid in the MPC in the manner of a classical thermosiphon. In this chapter, the thermal model of the HI-STAR 100 System is revisited with due recognition of the basket internal circulatory motion.

To expedite certification, this mode of heat dissipation was completely neglected in the currently licensed HI-STAR 100 System [2]. The modest heat loads (~20kW) permitted under the current HI-STAR Certificate of Compliance (CoC) reflect the consequence of Holtec's decision to shun carbon steel structural materials in favor of an all-alloy MPC construction and neglect of the thermosiphon effect. The reduction in heat dissipation of stainless steel baskets relative to carbon steel baskets is, however, not an irremediable situation. The thermosiphon cooling feature engineered in the HI-STAR MPC design more than compensates for the loss in the heat dissipation capacity caused by the replacement of carbon steel by stainless steel.

For continuity of presentation, a description of the HI-STAR 100 System thermal design features is provided in the next section. This is followed by an articulation of the HI-STAR thermal model for the MPC-24 with thermosiphon cooling included. The thermal model is consistent with the TN-24P benchmarked solution methodology presented in the preceding chapter. Peak cladding temperature values corresponding to different values of heat load, Q, are computed and reported in this chapter.

3.1 Thermal Design Features of HI-STAR 100

A sectional view of the HI-STAR 100 dry storage system is presented in Figure 3.1. The system consists of an MPC loaded into an overpack with a bolted closure plate. The fuel assemblies reside inside the MPC, which is sealed with a welded lid to form the confinement boundary. The MPC contains a stainless steel honeycomb basket structure that provides square-shaped fuel compartments (called cells) of appropriate dimensions to facilitate insertion of fuel assemblies. Each cell panel (except the periphery panels of the MPC-68) is provided with Boral thermal neutron absorber sandwiched between a sheathing plate and the cell panel along the entire length of the active fuel region. Prior to sealing the lid, the MPC is backfilled with helium. This provides a stable and inert environment for long-term storage of the SNF. The elevated helium pressure in the sealed MPC cavity supports thermosiphon cooling of the SNF in a manner described later in this section. Additionally, the annular gap formed between the MPC and the overpack is backfilled with helium. Heat is transferred from the SNF in a HI-STAR 100 System to the environment by passive heat transport mechanisms only.

An important thermal objective is to limit the peak maximum fuel cladding temperature to within safe limits. An equally important design criterion is to reduce temperature gradients within the MPC to minimize thermal stresses. In order to meet these design objectives, the HI-STAR 100 MPC basket is designed to possess certain distinctive characteristics, which are summarized in the following.

The MPC design minimizes resistance to heat transfer within the basket and basket periphery regions. This is ensured by an uninterrupted panel-to-panel connectivity realized in the all-welded honeycomb basket structure (Figure 3.1). Furthermore, the MPC design incorporates top and bottom plena with interconnected downcomer paths. The top plenum is formed by the gap between the bottom of the MPC lid and the top of the honeycomb fuel basket, and by elongated semicircular holes in each basket cell wall. The bottom plenum is formed by large elongated semicircular holes at the base of all cell walls. The MPC basket is designed to eliminate structural discontinuities (i.e., gaps) that introduce large thermal resistances to heat flow.

Consequently, temperature gradients are minimized in the design, which results in lower thermal stresses within the basket. Low thermal stresses are also ensured by an MPC design that permits unrestrained axial and radial growth of the basket to eliminate the possibility of thermally induced stresses due to restraint of free-end expansion.

[redacted]

[redacted]

[redacted]

As stated earlier, the complete thermal analysis is performed using the commercially available Computational Fluid Dynamics (CFD) code FLUENT [6]. The FLUENT CFD program is independently benchmarked and validated with a wide class of theoretical and experimental studies reported in the technical journals. Additionally, the solution methodology deployed to determine the thermal performance of a HI-STAR 100 System during long-term storage is fully consistent with the thermal model benchmarked in Chapter 2.

The HI-STAR 100 MPC basket designs consist of two distinct geometries to hold 24 PWR or 68 BWR fuel assemblies. The basket is a matrix of square compartments (called cells) to hold the fuel assemblies in a vertical position. The basket is a honeycomb structure of stainless steel plates with full-length edge-welded intersections to form an integral basket configuration. Individual cell walls (except outer periphery MPC-68 cell walls) are provided with Boral neutron absorber sandwiched between the cell wall and a sheathing plate over the full length of the active fuel region.

[redacted]

[redacted]

Subsections 4.4.1.1.1 through 4.4.1.1.11 of the HI-STAR TSAR [2] contain a systematic description of the mathematical models devised to articulate the temperature field in the HI-STAR 100 System. The mathematical models begin with the method to characterize the heat transfer behavior of the prismatic (square) opening referred to as the "fuel space" with a heat emitting fuel assembly situated in it. The methodology utilizes a finite-volume procedure to replace the heterogeneous SNF/fuel space region with an equivalent solid body having a well-defined temperature-dependent conductivity. The method to replace the "composite" walls of the fuel basket cells with an equivalent "solid" wall is also presented. Having created the mathematical equivalents for the SNF/fuel spaces and the fuel basket walls, the method to represent the MPC cylinder containing the fuel basket by an equivalent cylinder whose thermal conductivity is a function of the spatial location and coincident temperature is presented. In the following, an overview of the analysis methodology described in the HI-STAR TSAR [2] is provided for completeness.

3.2 Overview of the Thermal Model

Thermal analysis of the HI-STAR 100 System is performed by assuming that the system is subject to its maximum heat duty with each storage location occupied and with the heat generation rate in each stored fuel assembly equal to the design basis maximum value. While the assumption of equal heat generation imputes a certain symmetry to the cask thermal problem, the thermal model must incorporate three attributes of the physical problem to perform a rigorous analysis of a fully loaded cask:

i. [redacted]

ii. [redacted]

iii. [redacted]

[redacted]

[redacted]

In summary, appropriate finite-element models are used to replace the MPC cross section with an equivalent two-region homogeneous conduction lamina whose local conductivity is a known function of coincident absolute temperature. Thus, the MPC cylinder containing discrete fuel assemblies, helium, Boral, and stainless steel cell walls, is replaced with a right circular cylinder whose material conductivity will vary with the radial and axial position as a function of the coincident temperature.

The MPC-to-overpack gap is simply an annular space that is readily modeled with an equivalent conductivity that reflects conduction and radiation modes of heat transfer. The overpack is a radially symmetric structure except for the neutron absorber region, which is built from radial connectors and Holtite-A (see Figure 4.4.7 of the HI-STAR TSAR [2]). Using the classical equivalence procedure described in HI-STAR TSAR Section 4.4.1.1.6 [2], this region is replaced with an equivalent radially symmetric annular cylinder.

In this manner, a HI-STAR 100 System overpack containing a loaded MPC standing upright on the ISFSI pad is replaced with a right circular cylinder with spatially varying temperature-dependent conductivity. Heat is generated within the basket space in this cylinder in the manner of the prescribed axial burnup distribution. In addition, heat is deposited from insolation on the external surface of the overpack. Under steady state conditions the total heat due to internal generation and insolation is dissipated from the outer cask surfaces by natural convection and thermal radiation to the ambient environment. Details of the elements of mathematical modeling are provided in the HI-STAR TSAR [2].

3.3 FLUENT Model for HI-STAR 100 Temperature Field Computation

In the preceding section, a series of analytical and numerical models to define the thermal characteristics of the various elements of the HI-STAR 100 System were described. The thermal modeling begins with the replacement of the SNF cross-section and surrounding fuel cell space with a solid region with an equivalent conductivity. Since radiation is an important constituent of the heat transfer process in the SNF/storage cell space, and the rate of radiation heat transfer is a strong function of the surface temperatures, it is necessary to treat the equivalent region conductivity as a function of temperature. Because of the relatively large range of temperatures in a loaded HI-STAR 100 System under the design basis heat loads, the effects of variation in the thermal conductivity of materials with temperature throughout the system model are included. The presence of significant radiation effects in the storage cell spaces adds to the imperative to treat the equivalent storage cell lamina conductivity as temperature-dependent.

FLUENT finite-volume simulations have been performed to establish the equivalent thermal conductivity as a function of temperature for the limiting (thermally most resistive) PWR spent fuel types for the MPC-24. Utilizing the limiting SNF (established through a simplified analytical process for comparing conductivities) ensures that the numerical idealization for the fuel space effective conductivity is conservative for all non-limiting fuel types.

Having replaced the fuel spaces by solid square blocks with temperature-dependent conductivity essentially renders the basket into a non-homogeneous three-dimensional solid where the non-homogeneity is introduced by the honeycomb basket structure. The basket panels themselves are a composite of stainless steel cell wall, Boral neutron absorber, and stainless steel sheathing metal. This composite section is replaced with an equivalent "solid wall", as described in HI-STAR TSAR section 4.4.1.1.3 [2].

In the next step, a planar section of the MPC is considered. The MPC contains a non-symmetric basket lamina wherein the equivalent fuel spaces are separated by the "equivalent" solid metal walls. The space between the basket and the MPC, called the peripheral gap, is filled with helium gas and aluminum heat conduction elements. For conservatism, the added heat dissipation by the helium conduction elements in the peripheral gap are ignored. At this stage in the thermal analysis, the SNF/basket/MPC assemblage has been replaced with a two-zone cylindrical region whose thermal conductivity is a strong function of temperature.

The idealization for the overpack is considerably more straightforward. The overpack is radially symmetric except for the neutron absorber (Holtite-A) region. The procedure to replace the multiple shell layers, Holtite-A and radial connectors with equivalent solids utilizes classical heat conduction analogies, as discussed in Sections 4.4.1.1.6 and 4.4.1.1.9 of the HI-STAR TSAR [2].

In the final step of the analysis, the equivalent two-zone MPC cylinder, equivalent overpack shell, top and bottom plates, and ISFSI pad are assembled into a comprehensive finite-volume

[redacted]

model.

[redacted]

The emissivity applied to the external surfaces of the HI-STAR model accounts for radiation-blocking of the outer enclosure surface and no blocking for the overpack closure plate top surface. The MPC modeling on FLUENT, which features the internal natural circulation cooling, warrants a detailed description. Accordingly, the details of the MPC model are depicted in Figure 3.4. The essential features of the model, namely, the active and non-active fuel regions, bottom and top plenums, and downcomer space, are shown. This portion of the model is the same in the HI-STORM thermosiphon-enabled model discussed in Chapter 4 of this topical report. The active, non-active, and top/bottom plenum regions of the MPC cavity space are modeled as equivalent porous media regions for including the flow resistance characteristics of the regions. The porous media flow resistance characteristics for the fuel are computed for the Design Basis

W-17x17 fuel assembly (HI-STAR TSAR [2]). The downcomer region is modeled as an equivalent annular helium filled gap.

[redacted]

To the MPC thermosiphon model, the HI-STAR overpack conduction model is included with an MPC-to-overpack gap filled with helium. The exposed surfaces of the overpack dissipate heat to the ambient (at 80°F design basis maximum for long-term normal storage) by natural convection and radiation as well as being recipients of insolation heat. The combined overpack-MPC thermal model is deployed in determining steady state temperature fields in the HI-STAR 100 System MPC-24 cask.

3.4 HI-STAR Thermal Model Results

In this section, the results of the thermosiphon-enabled thermal analysis on the HI-STAR 100 cask considered in [2] are presented with the heat duty, Q, as the independent variable. The chief attributes of the problem are:

- HI-STAR 100 casks, each containing SNF emitting heat at a rate, Q, are spaced on a square grid at 12 ft pitch.
- Each cask is subject to insolation on its exposed surfaces with incident solar flux equal to 387 W/m^2 (12-hour CFR Part 71 [5] insolation averaged over a 24-hour period).
- Overpack enclosure shell insolation (including radiation blocking effect from surrounding casks) equal to 70 W/m^2.
- Each cask is situated on a 36" thick concrete slab (reference pad in the HI-STAR TSAR). The bottom of the pad is at a prescribed temperature of 60°F.

The solution of the above problem is presented herein using the thermal model described in the foregoing. This solution would reduce to the results presented in the HI-STAR TSAR [2] if the internal convection (thermosiphon) were suppressed and the aluminum heat conduction elements (which have been neglected in this solution) were included.

For purposes of this work, MPC-24 (used for PWR SNF) was selected. The object of this analysis is to compute the peak cladding temperature in the MPC for a specified heat load, Q. The permissible cladding temperature calculation is not included in this work, partly because the regulatory position in this matter in the HI-STAR 100 TSAR [2] and HI-STORM 100 TSAR [3]

is slightly different. Therefore, in this report, we limit ourselves to developing a curve between Q and the associated peak cladding temperature, T_c.

[redacted]

[redacted]

Table 3.1

W-17x17 OFA FUEL ASSEMBLY DATA

Parameter	Value
Array Size	17x17
Rod Diameter	0.36 inch
Rods Pitch	0.496 inch
Grid Strap Thickness	0.05 inch
Number of Grids	10
Cell Opening	8.75 inch

Table 3.2

PEAK CLAD TEMPERATURE (T_c) RESULTS (MPC-24)

	Temperature (°C [°F])					
Cavity Pressure (psia)	@Q = 20 kW		@Q = 25 kW		@Q = 30 kW	
50	335.6	[636]	397.4	[747.4]	455.2	[851.4]
75	286.6	[547.9]	343.6	[650.5]	398.8	[749.8]
100	255.7	[492.3]	305.8	[582.4]	355.4	[671.7]

Table 3.3

MPC-24 CAVITY AVERAGE TEMPERATURE (T)RESULTS

	Temperature (°C)		
Cavity Pressure (psia)	@ Q = 20 kW	@ Q = 25 kW	@ Q = 30 kW
50 psia	211.7	250.9	288.8
75 psia	188.9	223.3	257.3
100 psia	177.0	208.4	239.2

Table 3.4

HI-STAR 100 SYSTEM MPC-24 CAVITY PRESSURE PARAMETER (P_b')

	Helium Loading (g-mol/lit)		
Cavity Pressure (psia)	@ Q = 20 kW	@ Q = 25 kW	@ Q = 30 kW
50	30.37	28.06	26.17
75	47.75	44.44	41.59
100	65.35	61.09	57.41

Table 3.5

HI-STAR 100 SYSTEM MPC-24 CASK THERMAL RESULTS
AT DESIGN BASIS HELIUM LOADING

Cask Heat Load (kW)	Cavity Pressure (psia)	Peak Cladding Temperature (°C)
20	72.48	291.5
25	77.34	340.1
30	81.96	386.7

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FIGURE 3.1
CROSS SECTION ELEVATION VIEW OF HI-STAR 100 SYSTEM

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FIGURE 3.2
MPC-24 CROSS SECTION VIEW

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FIGURE 3.3
FLUENT THERMOSIPHON MODEL OF THE HI-STAR 100 MPC-24 CASK

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FIGURE 3.4
MPC-24 THERMAL MODELING DETAILS

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FIGURE 3.5
HI-STAR THERMOSIPHON ENABLED SOLUTION – MPC-24 PEAK CLADDING TEMPERATURE AS A FUNCTION OF HEAT LOAD

CHAPTER 4: HI-STORM 100 SYSTEM THERMOSIPHON-ENABLED THERMAL PERFORMANCE

4.0 Background

The HI-STORM 100 System is designed for long-term storage of spent nuclear fuel (SNF) in a vertical position. The SNF containing MPC internal basket design in combination with decay heat dissipation and gravity create conditions for the onset of fluid motion in the open internal cavity spaces. With the MPC emplaced in a vertical orientation within the overpack, the gravity acts in a most advantageous manner, causing an internal circulation of fluid within the MPC. In this chapter, the thermal model of the HI-STORM 100 System is revisited with full recognition of the basket internal circulatory motion of fluid. To expedite licensing, this mode of heat transfer was completely neglected in the initial certification of the HI-STORM 100 System.

Peak cladding temperature calculations for the HI-STORM System with a helium pressurized canister (MPC-24, 5 atm) have been recently performed by Pacific Northwest National Laboratory (PNNL) using the COBRA-SFS computer code. The results are documented in a communication from Tom Michener (PNNL) to the NRC staff (Attachment 1). These results pertain to a 21.5 kW decay heat load case parametrized by ambient temperature that was varied from 52°F to 250°F. To make a direct comparison, the HI-STORM thermal model (including the thermosiphon cooling) effect will be run with identical input data (heat load and ambient condition). The HI-STORM thermal performance parametrized by heat load is documented in a revised FSAR submittal to the NRC for a license amendment application (FSAR Report HI-2002444, Rev. 1, Docket 72-1014) and, therefore, is not produced in this report.

A description of the HI-STORM 100 System thermal design features is provided in the next section. This is followed by an articulation of the HI-STORM thermal model for the MPC-24 with thermosiphon cooling included. The thermal model is consistent with the TN-24P benchmarked solution methodology presented in Chapter 2 of this topical report. Peak cladding temperature results obtained from this model are reported and compared to the currently licensed HI-STORM cladding permissible temperature limits.

4.1 Discussion

A sectional view of the HI-STORM dry storage system is presented in Figure 4.1. The system consists of a sealed MPC emplaced inside a vertical ventilated storage overpack. Air inlet and outlet ducts that allow for air cooling of the stored MPC are located at the bottom and top, respectively, of the cylindrical overpack. The MPC consists of an all-alloy honeycomb basket structure that is identical to the HI-STAR 100 System MPC design. Transport of heat from the stored SNF to the outside environment is analyzed broadly in terms of three interdependent thermal models. The first two thermal models, which deal with heat transport from the fuel assemblies to the MPC shell periphery were described in Sections 3.1 and 3.2 of this report.

The third model deals with the transmission of heat from the MPC exterior surface to the external environment (heat sink). The upflowing air stream in the MPC/cask annulus extracts most of the heat from the external surface of the MPC, and a small amount of heat is radially deposited on the HI-STORM inner surface by conduction and radiation. Heat rejection from the outside cask surfaces to ambient air is considered by accounting for natural convection and radiative heat transfer mechanisms from the vertical (cylindrical shell) and top cover (flat) surfaces. The reduction in radiative heat exchange between cask outside vertical surfaces and ambient air, because of blocking from the neighboring casks arranged for normal storage at an ISFSI pad as described in Section 4.2, is recognized in the analysis. The overpack top plate is modeled as a heated surface in convective and radiative heat exchange with air and as a recipient of heat input through insolation. Insolation on the cask surfaces is based on 12-hour levels prescribed in 10CFR71, averaged over a 24-hour period, after accounting for partial blocking conditions on the sides of the overpack. The details are discussed in Section 4.4.1.1.8 of the HI-STORM FSAR [3].

Subsections 4.4.1.1.1 through 4.4.1.1.9 of the HI-STORM FSAR [3] contain a systematic description of the mathematical models devised to articulate the temperature field in the HI-STORM System. The description begins with the method to characterize the heat transfer behavior of the prismatic (square) opening referred to as the "fuel space" with a heat emitting fuel assembly situated in it, followed by the method to replace the "composite" walls of the fuel

basket cells with an equivalent "solid" wall. Having created the mathematical equivalents for the SNF/fuel spaces and the fuel basket walls, the method to represent the MPC cylinder containing the fuel basket by an equivalent cylinder whose thermal conductivity is a function of the spatial location and coincident temperature is presented.

Following the approach of presenting descriptions starting from the inside and moving to the outer region of a cask, the next subsection presents the mathematical model to simulate the HI-STORM System.

4.2 Global HI-STORM Thermal Analysis Model

The global HI-STORM thermal model consists of two interconnected subsystem models, namely that of the MPC and the HI-STORM overpack. The MPC thermal model, with thermosiphon cooling included, which is described in Chapter 3, is adopted in the global HI-STORM model. In the MPC subsystem model, heat dissipation by the aluminum heat conduction elements in the basket periphery region is completely neglected in the interest of conservatism. The HI-STORM overpack thermal model is described next.

The thermal model for the HI-STORM overpack is prepared as a two-dimensional axisymmetric body. For this purpose, the hydraulic resistances of the inlet ducts and outlet ducts, respectively, are represented by equivalent axisymmetric porous media. The axial resistance to airflow in the MPC/overpack annulus (which includes longitudinal channels to "cushion" the MPC structure during a postulated non-mechanistic tip-over event) is replaced by a hydraulically equivalent annulus. The surfaces of the ducts and annulus are assumed to have a relative roughness (ε) of 0.001. This value is appropriate for rough cast iron, wood stave and concrete pipes, and is bounding for smooth painted surfaces (all internal and external HI-STORM overpack carbon steel surfaces are painted). Finally, it is necessary to describe the external boundary conditions to the overpack situated on an ISFSI pad. An isolated HI-STORM will take suction of cool air from, and reject heated air to, a semi-infinite half-space. In a rectilinear HI-STORM array, however, the unit situated in the center of the grid is evidently hydraulically most disadvantaged, because of potential interference to air intake from surrounding casks (Figure 4.3). To simulate this condition in a conservative manner, we erect a hypothetical cylindrical barrier around the

centrally local HI-STORM. The radius of this hypothetical cylinder, R_o, is computed from the equivalent cask array downflow hydraulic diameter (D_h) which is obtained as follows:

$$D_h = \frac{4 \; x \; Flow \; Area}{Wetted \; Perimeter}$$

$$= \frac{4 \, (A_o - \frac{\pi}{4} d_o^{\,2})}{\pi \, d_o}$$

where:

A_o = Minimum tributary area ascribable to one HI-STORM (346 ft^2)

d_o = HI-STORM overpack outside diameter

The hypothetical cylinder radius, R_o, is obtained by adding half D_h to the radius of the HI-STORM overpack. In this manner, the hydraulic equivalence between the cask array and the HI-STORM overpack to hypothetical cylindrical annulus is established.

The internal surface of the hypothetical cylinder of radius R_o surrounding the HI-STORM module is conservatively assumed to be insulated. Any thermal radiation heat transfer from the HI-STORM overpack to this insulated surface will be perfectly reflected, thereby bounding radiative blocking from neighboring casks. Then, in essence, the HI-STORM module is assumed to be confined in a large cylindrical "tank" whose wall surface boundaries are modeled as zero heat flux boundaries. The air in the "tank" is the source of "feed air" to the overpack. The air in the tank is replenished by ambient air from above the top of the HI-STORM overpacks. There are two sources of heat input to the exposed surface of the HI-STORM overpack. The most important source of heat input is the internal heat generation within the MPC. The second source of heat input is insolation, which is conservatively quantified in the manner described in the HI-STORM FSAR [3].

The FLUENT model consisting of the axisymmetric 3-D MPC space, the overpack, and the enveloping tank is schematically illustrated in Figure 4.2. The HI-STORM thermosiphon-enabled solution is computed in a two-step process. In the first step, a HI-STORM overpack

thermal model computes the ventilation effect from annulus heating by MPC decay heat. In this model, heat dissipation is conservatively restricted to the MPC shell (i.e., maximize rate of annulus heating by *completely* neglecting heat dissipation from MPC lid and baseplate). The HI-STORM overpack thermal model is depicted in Figure 4.4 showing these modeling constructs. Maximizing the rate of annulus heating has the effect of overstating the annulus air, concrete and MPC shell temperatures. The MPC shell temperature profile (from A to B, as shown in Figure 4.4) computed by the overpack model is bounded by an enveloping linear variation (ELV) as shown in Figure 4.5 for 80°F ambient temperature and 21.5 kW heat load. In this model, heat input due to insolation is applied to the top surface of the HI-STORM overpack and to the exposed cylindrical surface with a bounding maximum solar absorbtivity equal to 1.0. The most disadvantageously placed cask (i.e., one subject to maximum radiative blocking) is modeled.

The ELV is used in the second step as an MPC shell boundary condition to compute the temperature field of the stored fuel in a pressurized helium environment (5 atm pressure). In this MPC model, the HI-STORM overpack that was evaluated in the first step is excluded. For including the effect of heating of HI-STORM overpack ends by heat dissipation from MPC lid and baseplate, the HI-STORM lid and bottom portions are included in the HI-STORM MPC model. Heat dissipation from the overpack annulus inner surfaces below and above the MPC shell region from A to B (see Figure 4.6) are modeled as mixed (convection and radiation) bounding conditions.

The bottom surface of the overpack, in contact with the ISFSI pad, rejects heat through the pad to the constant temperature (77°F) earth below. In Table 4.1, the principal HI-STORM 100 System thermal analysis parameters are presented for ready reference.

4.3 HI-STORM Thermal Model Results

As described in the previous subsection, a two-step HI-STORM System thermal modeling process is used to compute the peak cladding temperature response. The ELV temperature profiles are generated for four ambient temperature levels, viz., 52° F, 80° F, 150° F and 250° F. These profiles are then used as modeling inputs to the MPC helium internal circulation model

and peak cladding temperatures computed for 21.5 kW heat load and 5 atm helium pressure. In Figure 4.7, a comparison of the HI-STORM model solution with PNNL COBRA-SFS is graphically depicted. From this figure, it is evident that the thermal model for HI-STORM 100 produces conservative results.

Table 4.1

PRINCIPAL HI-STORM THERMAL ANALYSIS PARAMETERS

Ambient Temperature	80°F
Concrete Pad thickness	36"
Beneath Pad Soil Temperature	77°F
Overpack Lid Insolation	387 W/m^2*
Overpack Curved Surface Insolation	83 W/m^2†

* CFR Part 71 [5] 12-hour insolation averaged over a 24-hour day.

† Including radiation blocking effects by surrounding casks.

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FIGURE 4.1
HI-STORM 100 OVERPACK WITH MPC PARTIALLY INSERTED

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FIGURE 4.2
SCHEMATIC DEPICTION OF THE HI-STORM THERMAL ANALYSIS

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FIGURE 4.3
ILLUSTRATION OF MINIMUM AVAILABLE PLANAR AREA PER
HI-STORM MODULE AT AN ISFSI

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FIGURE 4.4

HI-STORM OVERPACK THERMAL MODEL

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FIGURE 4.5

MPC SHELL TEMPERATURE PROFILE (21.5 kW, 80F AMBIENT)

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FIGURE 4.6
HI-STORM MPC HELIUM CIRCULATION MODEL

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FIGURE 4.7
COMPARISON OF FLUENT PEAK CLAD TEMPERATURE SOLUTION
WITH PNNL RESULT

CHAPTER 5: CLOSURE

The NRC's governing regulatory document on dry storage (NUREG-1536) published in 1997 explicitly recognizes internal convection (thermosiphon) as a regulationally acceptable heat transport mechanism. In a round table meeting sponsored by NEI on July 1, 1998, the NRC's staff further clarified the Commission's position in this matter, stating in a written text, "Although this method departs from previously approved applications, the NRC welcomes new and different approaches to analyze a package's heat transfer given that the appropriate experimental data is provided and used as a benchmark for the mixed modes of heat transfer". This regulatory position set the stage for Holtec International to revise the thermal analysis of the company's HI-STAR 100 and HI-STORM 100 Systems, both of which utilize a common set of multi-purpose canisters expressly designed to induce internal recirculation of the contained helium gas.

At this writing, Holtec's Safety Analysis Reports on the HI-STAR 100 and HI-STORM 100 Systems, without thermosiphon credit, have been reviewed and accepted by the USNRC. The thermal analysis methodology in both SARs is exactly the same. With an eye to the day when the thermosiphon effect would gain regulatory legitimacy, Holtec built the thermal analysis model on the commercially available computer code FLUENT, which is capable of simulating all three modes of heat transfer. The HI-STAR/HI-STORM thermal model implemented on FLUENT, however, was executed with the "thermosiphon disabled" (by setting the gravity vector = 0 in the code) to secure HI-STAR 100 and HI-STORM 100 certification. The regulatory acceptance of mixed mode heat transfer in MPCs unfetters Holtec's systems from this excessively conservative assumption.

Enabling the gravity vector in the FLUENT model is a necessary step for the thermosiphon action to manifest itself in the thermal solution. First, however, the veracity of the thermal model with thermosiphon enabled, had to be established *beyond a shade of doubt,* so that it could be used as a licensing vehicle for HI-STAR/HI-STORM heat duty uprates.

Fortunately, the path to validate the HI-STAR/HI-STORM thermal model was paved by a consortium of companies led by EPRI and PNL, who in the 1980s conducted a remarkably comprehensive set of thermal tests on a full-size cask loaded with real-life commercial spent nuclear fuel (from Surry). The cask, identified as the TN-24P, was specifically engineered to facilitate internal thermosiphon. The temperature data was meticulously recorded and published in an EPRI report [1]. In order to validate the enhanced thermal solution (i.e., thermosiphon enabled), it was benchmarked against the EPRI test data. As we show in Chapter 2 of this topical report, the benchmarking studies are uniformly successful. The HI-STAR/HI-STORM thermal model, when applied to the TN-24P cask, is seen to overpredict the fuel cladding temperature with modest conservatism with respect to the measured data in every case (cask oriented vertically and horizontally, helium and nitrogen as inert gas, vacuum condition). Details of the correlation of the FLUENT model with EPRI's test data are presented in Chapter 2 of this report.

This "benchmarked" thermal model is next applied to predict the thermal performance of the HI-STAR 100 System loaded with an MPC-24 (PWR fuel). The end product of this study is a heat load, Q, vs. peak SNF temperature, T_c, curve. In performing the HI-STAR thermal analysis, however, a significant new conservative assumption was made. This conservatism pertains to the so-called "aluminum heat conduction elements" (AHCE). The AHCEs are formed shapes of aluminum installed in the space between the fuel basket and the MPC shell to provide a heat conduction path between the basket and the MPC shell. In the presence of the thermosiphon effect, which provides a convective connection between the basket and the shell, the AHCEs no longer serve a critical bridge for heat transmission out of the fuel basket. They will, however, continue to provide a parallel heat transfer path, thus, in effect, increasing the total heat dissipation rate. In the interest of conservatism, the contribution of the AHCEs is neglected in the HI-STAR thermal model utilized in Chapter 3.

Chapter 4 contains the thermal performance information on HI-STORM 100 at a fixed* heat load (21.5 kW). The thermal model for both systems is identical (including the neglect of AHCEs)

* HI-STORM performance parametrized by heat load is documented in the latest (Rev. 1) FSAR [3].

except for their physical differences, most notably the fact that HI-STORM 100 (unlike HI-STAR 100) is a ventilated system.

Despite the conservatisms in the revised thermal model, which are clearly discernible in the benchmark comparisons (Chapter 2), heat transfer rates in both the HI-STAR 100 and the HI-STORM 100 are considerably enhanced when the contribution of the internal thermosiphon in the MPC is incorporated. The heat duty Q vs. peak cladding temperature T_c curves presented in this report for the HI-STAR 100 can be used to redefine the design basis heat loads and to secure the appropriate amendments to their CoCs.

In conclusion, this topical report does not address several associated thermal issues required for a certificate amendment, namely, the recharacterization of the cask's thermal behavior during vacuum drying operations, during a fire event, and in the aftermath of dilution of the helium cover gas by the release of the fission gases. These and other analyses currently reported in the HI-STAR 100 and HI-STORM 100 TSARs will need to be appropriately revised in the system TSAR. This topical report's principal objective was to benchmark and validate the mixed mode heat transfer model for the HI-STAR/HI-STORM Systems by comparison with a robust set of experimental data collected in a national program by third-party reputable organizations. In addition, a comparison with the numerical results obtained by PNNL using a completely independent model is also performed. The quantification of the thermal performance of the HI-STAR/HI-STORM Systems under normal condition of storage presented in this topical report helps to establish the contribution of internal convection in the MPCs in these systems using the benchmarked thermal model.

CHAPTER 6: REFERENCES

[1] "The TN-24P PWR Spent Fuel Storage Cask: Testing and Analyses", by the Pacific Northwest Laboratory, et al., EPRI NP-5128, April 1987.

[2] "Topical Safety Analysis Report for Holtec International Storage Transport and Repository Cask System (HI-STAR 100 Cask System)", NRC Docket No. 72-1008, Holtec Report HI-941184, Volumes I and II, Rev. 10.

[3] "Final Safety Analysis Report for the Holtec International Storage and Transfer Operation Reinforced Module Cask System (HI-STORM 100 Cask System)", NRC Docket No. 72-1014, Holtec Report HI-2002444, Rev 1.

[4] Rohsenow, W.M. and Hartnett, J.P., "Handbook of Heat Transfer", McGraw Hill book Company, New York, 1973.

[5] 10CFR71, "Packaging and Transportation of Radioactive Material", 1-1-96 Edition.

[6] FLUENT Computational Fluid Dynamics Software (Fluent, Inc., Centerra Resource Park, 10 Cavendish Court, Lebanon, NH-03766).

[7] Benjamin, A.S., McCloskey, D.J., Powers, D.A., Dupree, S.A., "Spent Fuel Heatup Following Loss of Water During Storage", NUREG CR-0649, SAND77-1371, R-3, (March 1979).

[8] ANSYS Finite Element Modeling Package, Swanson Analysis System, Inc.

[9] NUREG-1536, "Standard Review Plan for Dry Cask Storage Systems", USNRC, January1997.

APPENDIX A

VALIDATION OF FLUENT WITH OTHER THEORETICAL SOLUTIONS AND EXPERIMENTAL DATA

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ATTACHMENT 1

PNNL HI-STORM THERMAL EVALUATION

Pacific Northwest
National Laboratory
Operated by Battelle for the
U.S. Department of Energy

EXHIBIT
STAFF - "E"

May 31, 2000

Jack Guttmann
U.S. Nuclear Regulatory Commission
NMSS/SFPO/TRD, 13 D13
One White Flint North
11555 Rockville Pike
Rockville, MD 20852-2738

Dear Jack:

Please find attached a copy of the summary letter report "TEMPEST Analysis of the Utah ISFSI Private Fuel Storage Facility And COBRA-SFS Analysis of the Holtec Hi-Storm 100 Storage system."

If you have further questions or comments, please contact me.

Sincerely,

Thomas E. Michener

Thomas E. Michener
Sr. Research Engineer

TEM:cm

cc: File/lb

902 Battelle Boulevard • P.O. Box 999 • Richland, WA 99352

Telephone (509) 375-2162 ▪ Email tom.michener@pnl.gov ▪ Fax (509) 375-3865

Summary Report:

TEMPEST Analysis of the Utah ISFSI Private Fuel Storage Facility And COBRA-SFS Analysis of the Holtec Hi-Storm 100 Storage system

Background:

At the request of the U.S. Nuclear Regulatory Commission, the staff at the Pacific Northwest National Laboratory (PNNL) analyzed the thermal performance of the Private Fuel Storage Facility in Utah (PFS) using the TEMPEST computational fluid dynamics software. A 3-dimensional section of PFS with a total of 20 casks was modeled, using conservative assumptions, to estimate the flow field and temperature distributions surrounding the casks. The results from this model were then extracted and used as the boundary temperature for a detailed analysis of an individual Holtec Hi-Storm 100 cask system. The Holtec cask was modeled using the COBRA-SFS (Spent Fuel Storage) thermal hydraulic computer software. The analyses assumed bounding fuel and solar energy (insolation) conditions and natural circulation (convection) cooling inside the multi-purpose canister (MPC). A summary description of the approaches taken and the results from each effort are provided below.

TEMPEST PFS Site Calculation:

A 3-dimensional TEMPEST model was developed to simulate a strip of twenty casks, which is believed to represent the hottest row of casks in the proposed PFS array. The TEMPEST code has been extensively used by US Government agencies to model near and far field plumes, among many other 3-D applications. The modeled region is shown in a planar view in Figure 1. The 3-D computational model consisted of a strip 30 ft wide, 443 ft long and 200 ft in elevation. As shown in Figure 1, the modeled region extends from the array center (hottest point) to about 110 ft beyond the edge of the array. Adiabatic boundaries were assumed at three of the four sides surrounding the strip. The source of ambient air available to the casks in this model is from above or from the end of the row of casks.

The insolation load was assumed to be 123 Btu/ft^2-hr (388 W/m^2) on the flat surfaces such as the gravel roadway, concrete pads, and cask lids. Absorptivities were obtained from the book: "Thermal Radiation Heat Transfer" by Siegel and Howell. The values were 0.29 for the gravel roadway, 0.73 for the concrete pads, and 0.75 for the steel cask lids. The design base fuel load used in the TEMPEST calculation was 21.5 kW per cask. This heat load corresponds to the hotter MPC-68 design, which may be located at the PFS facility.

The TEMPEST model was executed until steady-state 3-dimensional velocity, temperature, and pressure fields were achieved. Results of this simulation revealed a complex 3-dimensional flow and temperature field typical of interacting thermal plumes

in the open environment. One noteworthy conclusion is that a large amount of "far field" ambient air is induced into the system. The ambient air is entrained into the cask array by the rising thermal plume. This can be seen by referring to Figures 2a and 2b. Also, the volume of air drawn into the cask inlet vents and ejected out the exit vents is relatively negligible compared to the volume of air entrained into the rapidly rising plume flow.

The results also show that there is a significant downward and lateral circulation of ambient air in the vicinity of the gravel roadway center along the row of casks. This circulation is caused by air inducted into the turbulent plume, which is rapidly flowing above the row of casks. A fresh supply of cool ambient air travels down the path formed by the gravel roadway . This cool flow prevents a build-up of high temperature air just above the surface of the gravel roadway.

To ensure that the calculated heat transfer from the insolated surfaces (gravel roadway, etc) was conservative, heat transfer coefficients were chosen that are greater than one order of magnitude larger than best estimate values. The TEMPEST results show that greater than 90% of the insolation heat load is transported to the air that flows adjacent to heated surface. Radiation heat loss from the horizontal surfaces was not considered, thereby maximizing the heat that is convected to the air.

Computed results show that the average hottest air (mixed-mean temperature per cask) entering into any cask's inlet vents is 60.44 °F, an increase of approximately 8°F above the far field ambient temperature.

<u>COBRA-SFS Cask Calculation:</u>

A 1/8 symmetry section (Figure 3) of the Holtec Hi-Storm 100 spent fuel storage system was modeled using the COBRA-SFS computer code. The Hi-Storm system consists of a canister surrounded by a concrete overpack. The COBRA-SFS code modeled in detail the flow field in the canister, accounting for conduction, convection, and thermal radiation heat transfer mechanisms.. The code has been rigorously validated against full scale experimental data for various cask designs, including ventilated concrete casks similar to the Hi-Storm design. Therefore the code has been validated to model flow in the annulus formed between the cask canister and the concrete overpack. Using these capabilities, the calculations treated the heat transfer throughout the cask internals, (fuel assemblies, basket, and flow channels) into and across the annulus, out the vents to ambient, through the concrete overpack and out to ambient. All of the COBRA-SFS simulations included insolation heat input on the cask sides and lid.

Cases 1-8 (Table 1) were investigated for a cask loaded with 24 PWR spent fuel assemblies with 0.896 Kilowatts (kW) per assembly, for a total of 21.5 kW of decay heat. This total decay heat is actually higher than the design limit of 20.88 kW. Therefore, the calculated PCT for Cases 1-8 are conservatively high. Two additional cases quantified the impact of using the correct decay heat.. Case 9 repeats Case 2 with the a decay heat load of 20.88 kW and Case 10 repeats Case 8 with the corrected decay heat load.

COBRA-SFS Predicted

Case#	Internal pressure of Helium at 5 ATM	Peak Clad Temperature
	(21.5 kW decay heat)	
1	Ambient air at 52°F	534 °F
2	Ambient air at 60°F	543 °F
3	Ambient air at 67°F	550 °F
4	Ambient air at 80°F	563 °F
5	Ambient air at 125°F	608 °F
6	Ambient air at 150°F	631 °F
7	Ambient air at 200°F	680 °F
8	Ambient air at 250°F	724 °F
	(20.88 kW decay heat)	
9	Ambient air at 60°F	531 °F
10	Ambient air at 250°F	713 °F

Table 1. Summary of COBRA-SFS simulations

A plot of the COBRA-SFS predicted Peak Clad Temperature (PCT) vs. ambient temperature at inlet vents is shown in Figure 4 for Cases 1-10. The calculation that simulates the long term conditions for the PFS facility case is Case 9, which uses results from the TEMPEST simulation (60°F) as the ambient temperature boundary condition and the corrected decay heat load of 20.88 kW.

Conclusions:

The impact of neighboring casks on the average air temperature entering the limiting HI-STORM cask at the PFS facility is negligible (approximately 8 °F above the "far field" ambient temperature) given the extensive margin in the cask design. The HI-STORM 100 system is designed to take advantage of convection cooling inside the MPC. This design leads to a calculated margin that permits approximately 173 °F increase in the "far field" ambient temperature (or an air temperature of 225 °F) to enter the inlet vents of the MPC before exceeding the NRC approved maximum allowable temperature limit of 692°F. In reality, a larger margin exists if the applicant credited a less conservative, but bounding, fuel rod pressure when evaluating the maximum allowable temperature limit. The margin is also increased if site-specific insolation values and view factors were used. An additional conservatism used in the analysis is the use of design basis fuel for every assembly in the MPC.

Given the margin for the air temperature at the cask inlet vent, a similar margin exists for the calculated maximum fuel rod temperature. A minimum of 161 °F (692-531) margin exists between the calculated PCT and the HI-STORM approved maximum allowable temperature limit. From these calculations, it is concluded that the HI-STORM 100 system meets the thermal regulatory requirements set in 10CFR Part 72 with ample margin.

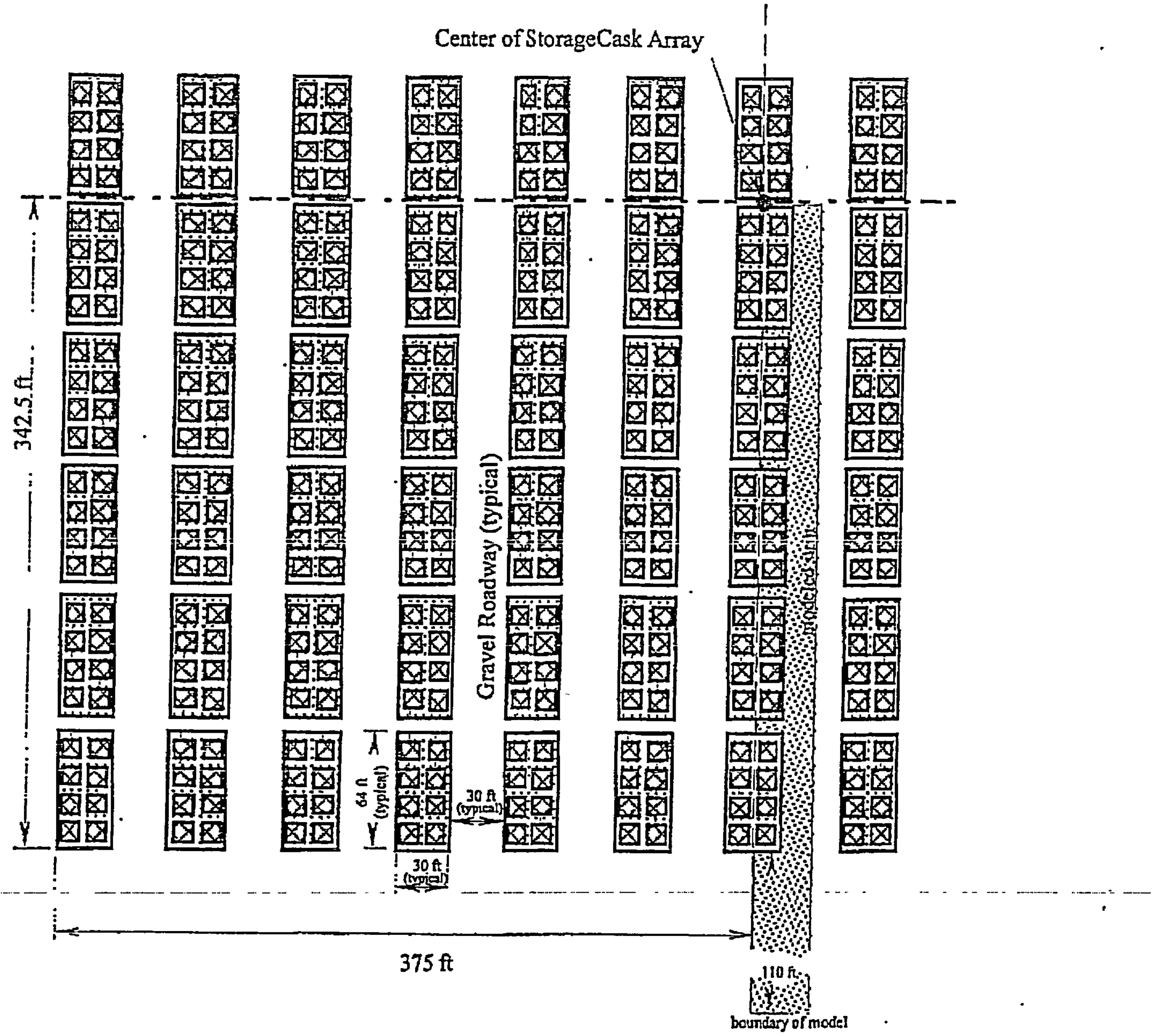


Figure 1. Planar Schematic: TEMPEST model of Utah PFS

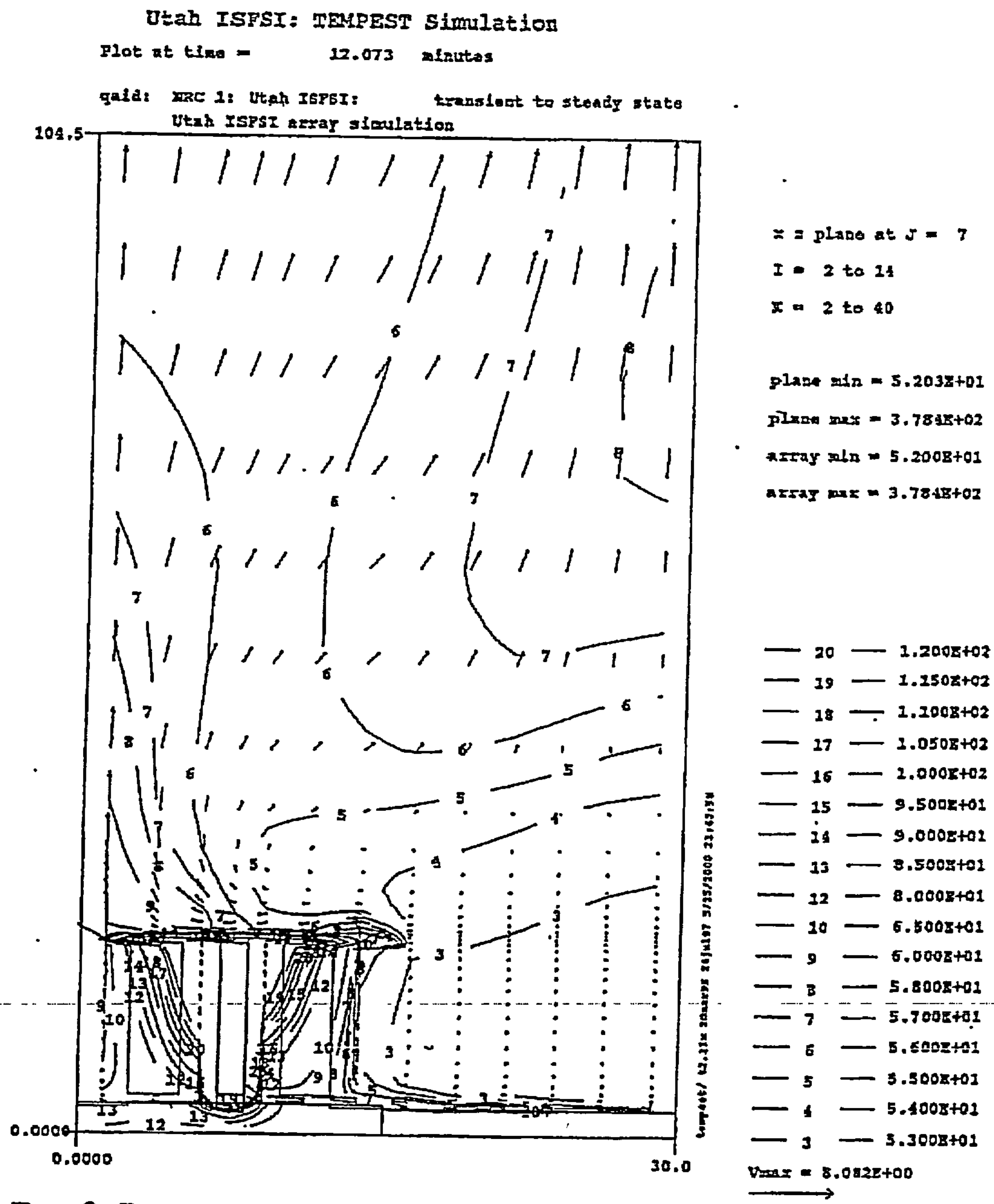


Figure 2a. Temperature Contours and Velocity Vectors in Vertical Plane Though Center Cask Centerline

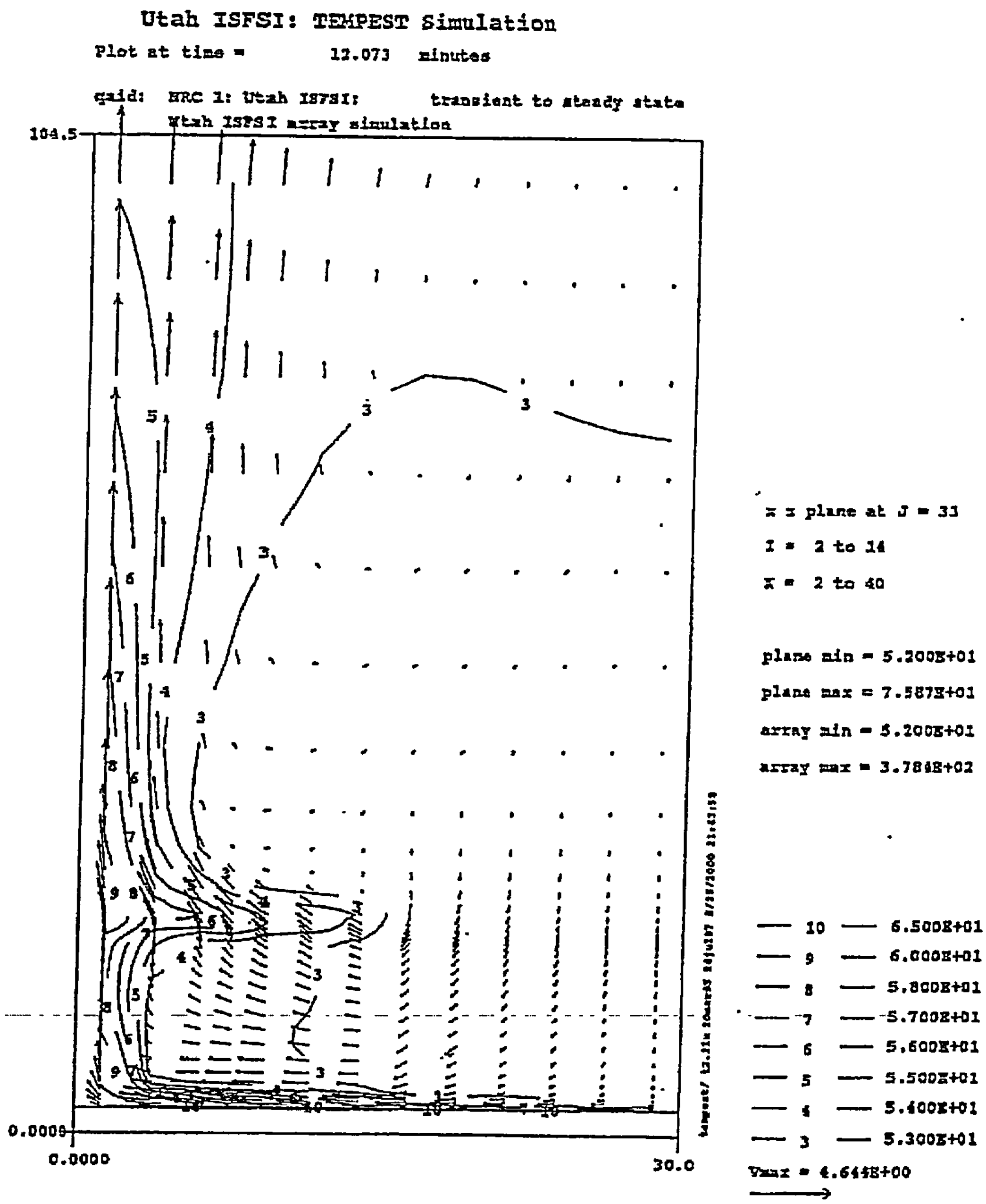


Figure 2b Temperature Contours and Velocity Vectors in Vertical Plane Between Two Pads

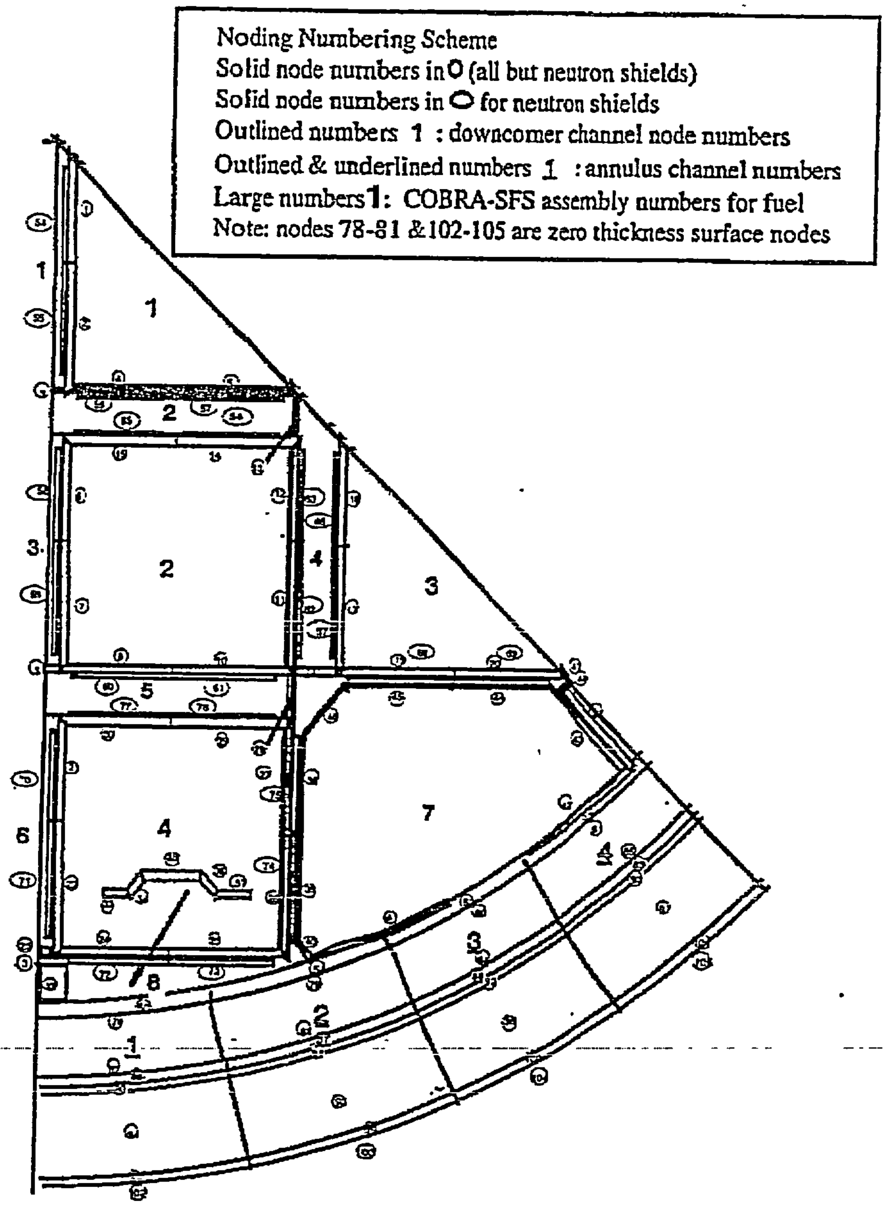


Figure 3. COBRA-SFS 1/8 Symmetry Hi-Storm Cask Node Map

NOT TO SCALE

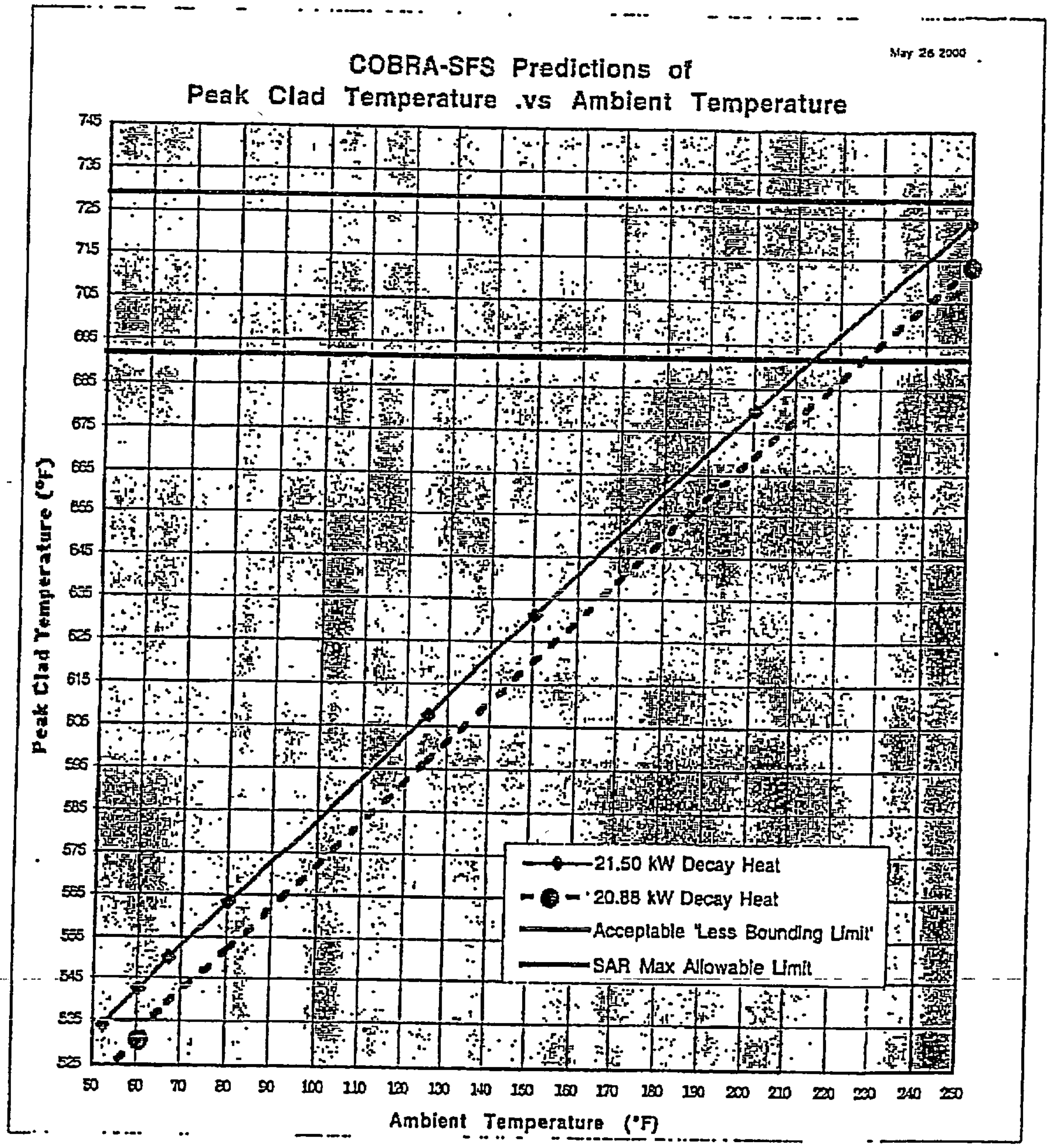
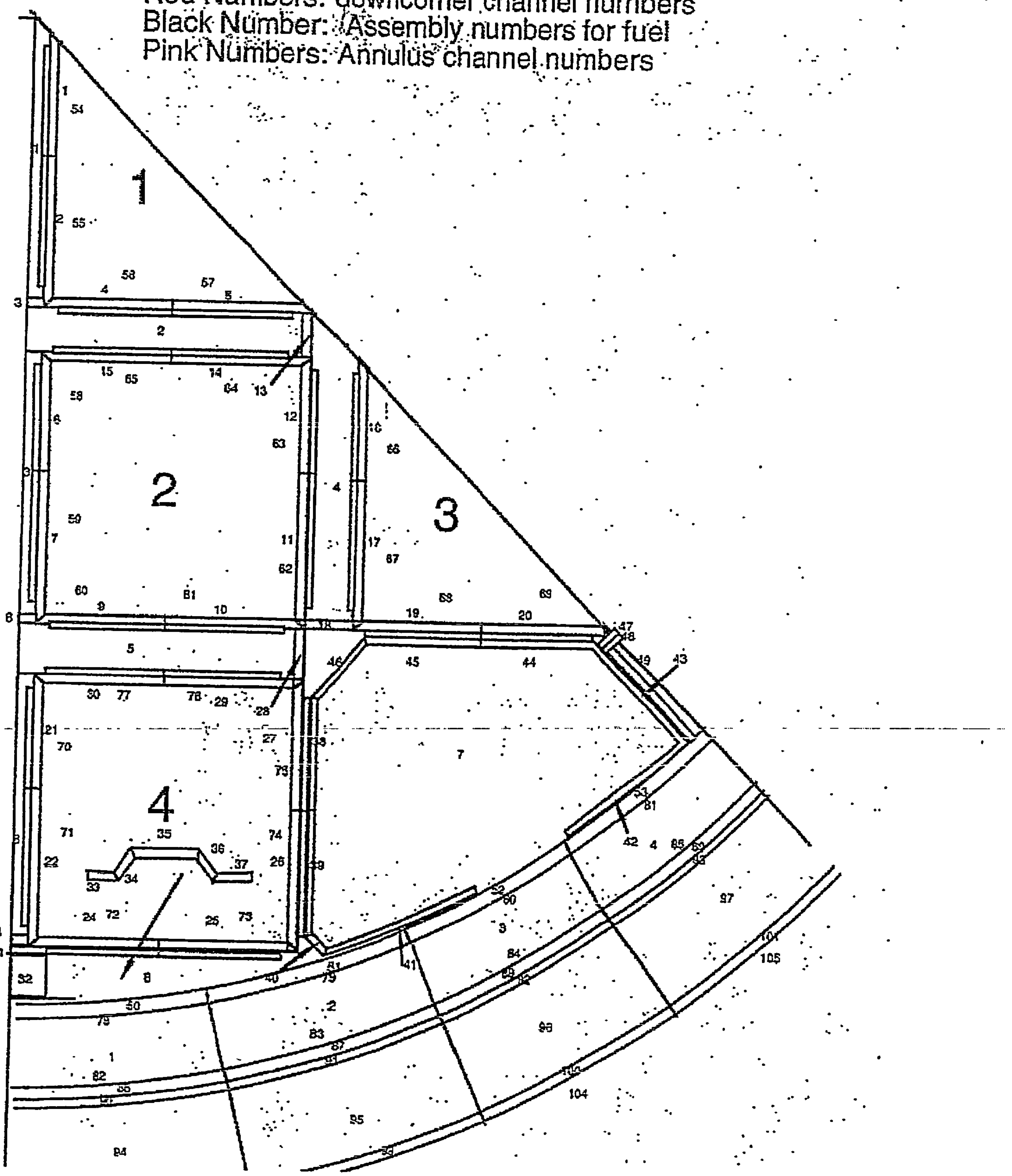
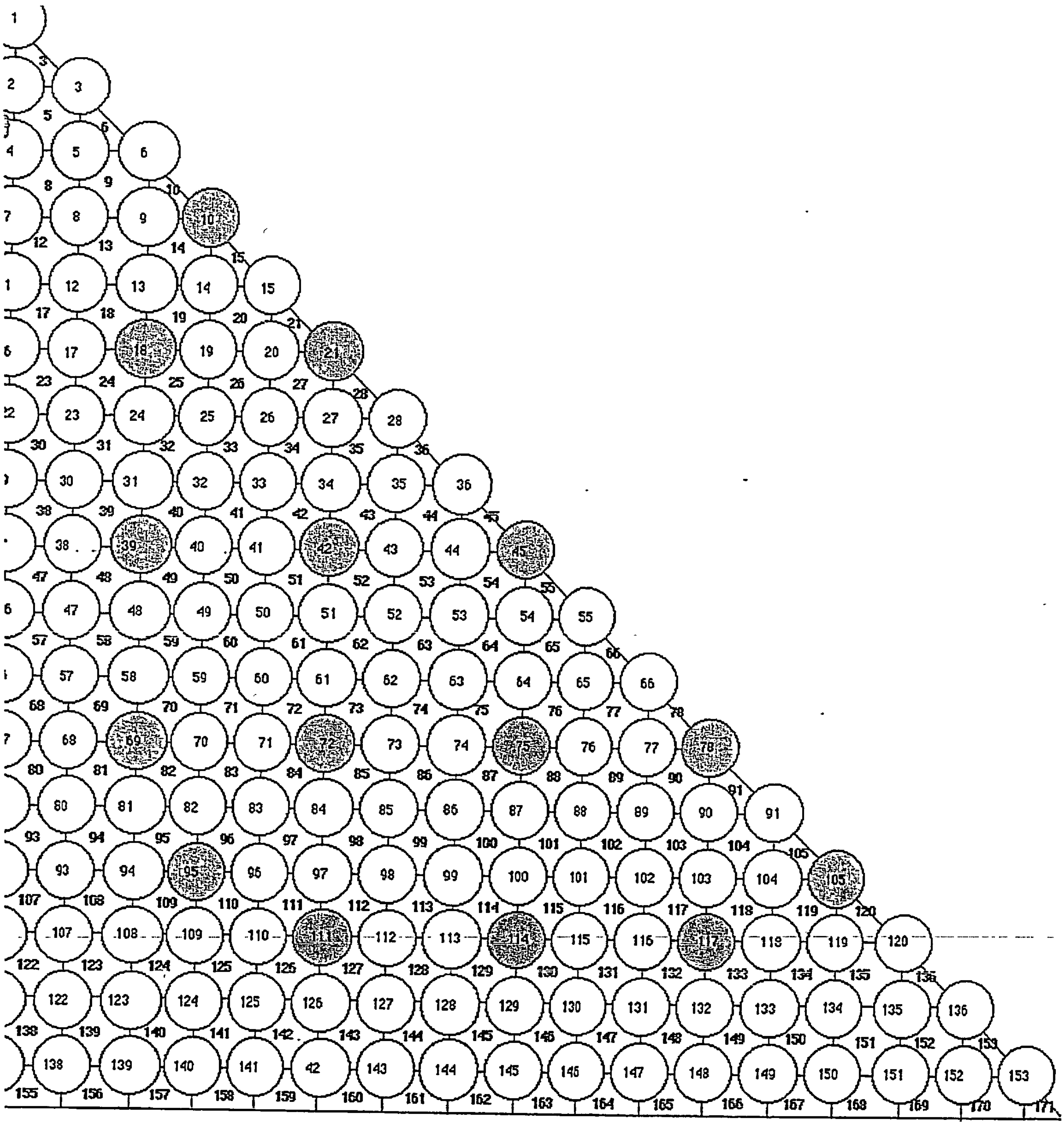


Figure 4. COBRA-SFS PCT vs Ambient Temperature

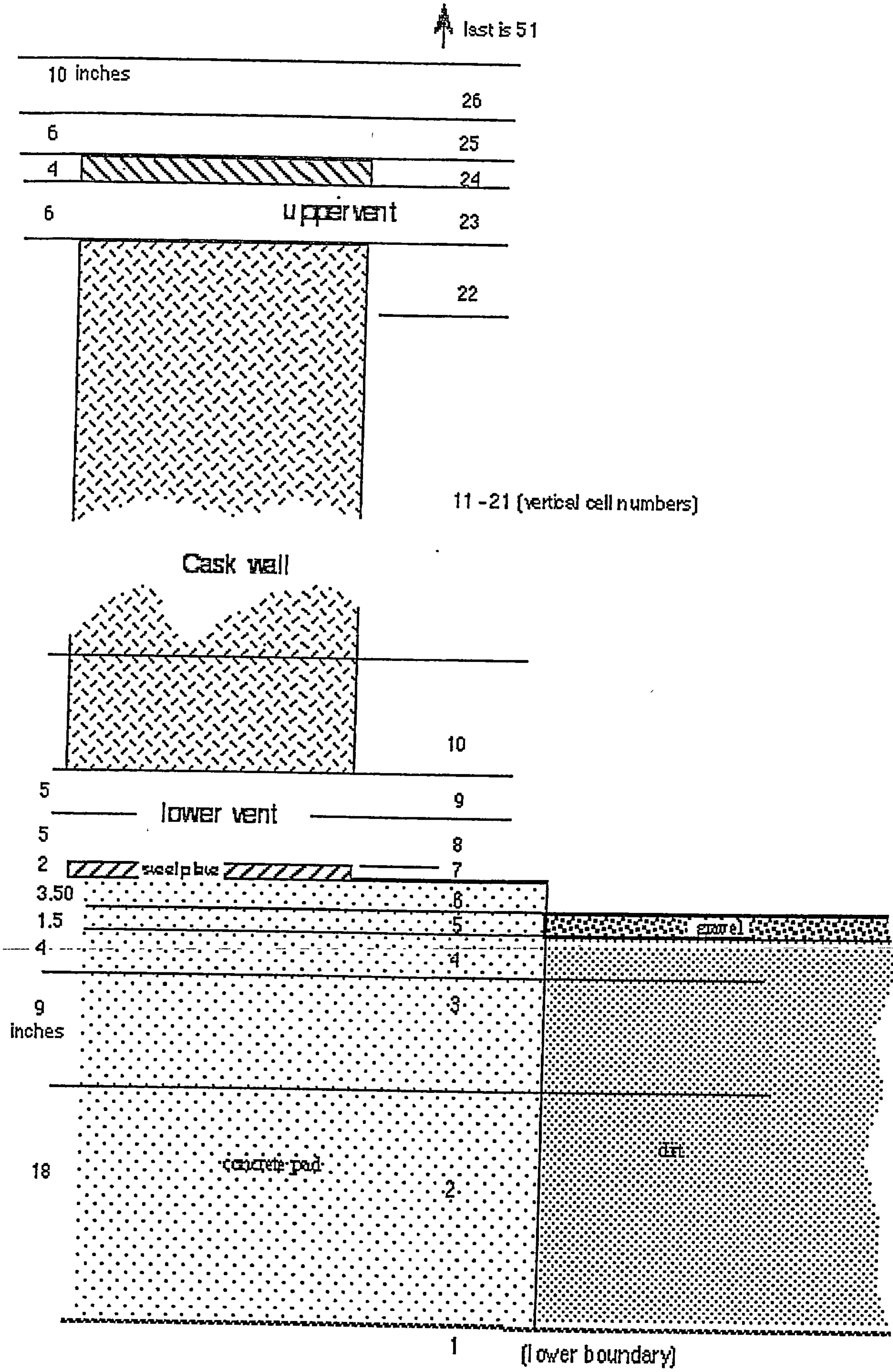
COBRA-SFS

Green Numbers: solid node numbers (all but nuetron schields)
Blue Numbers: solid node numbers for nuetron schield
Red Numbers: downcomer channel numbers
Black Number: Assembly numbers for fuel
Pink Numbers: Annulus channel numbers



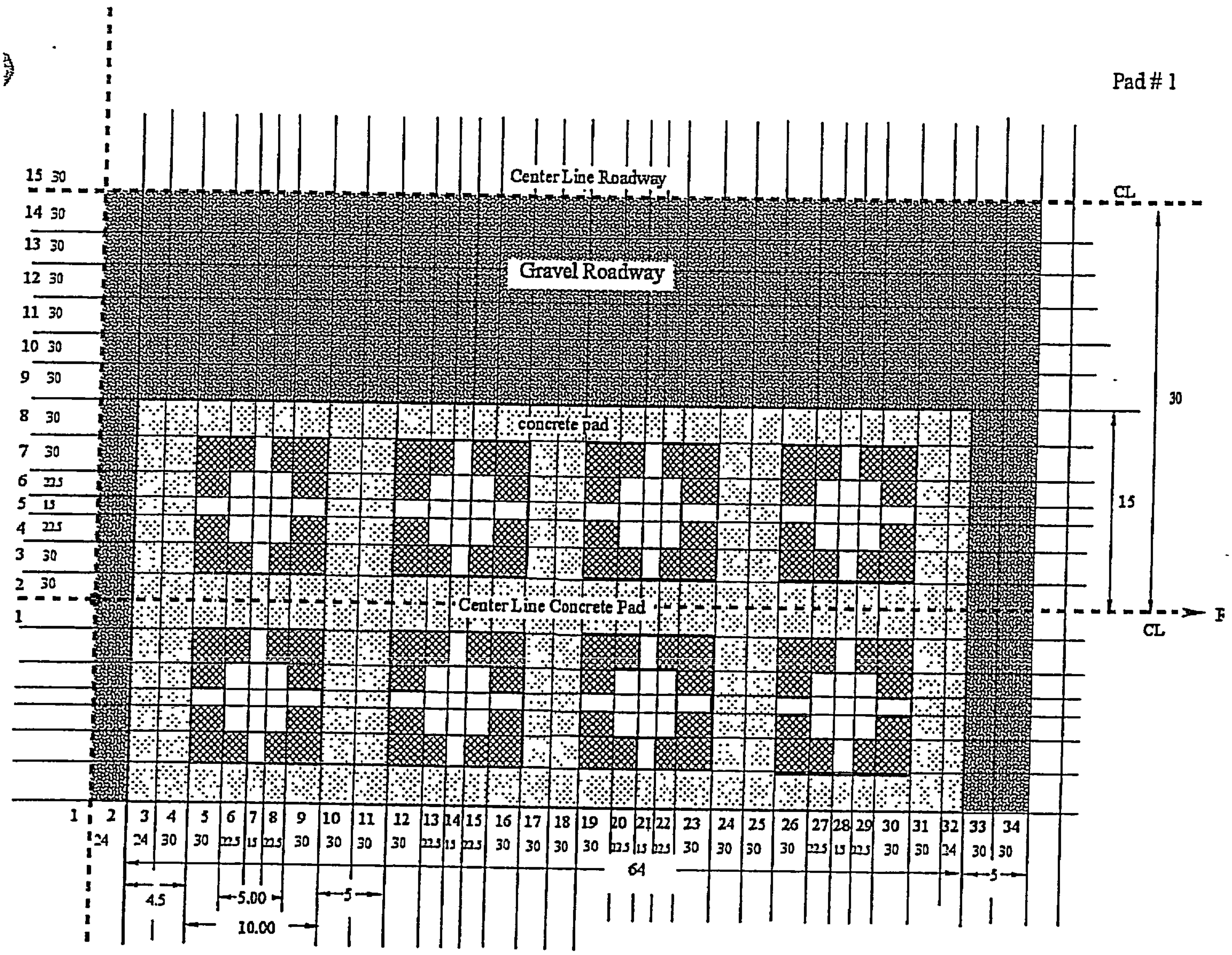


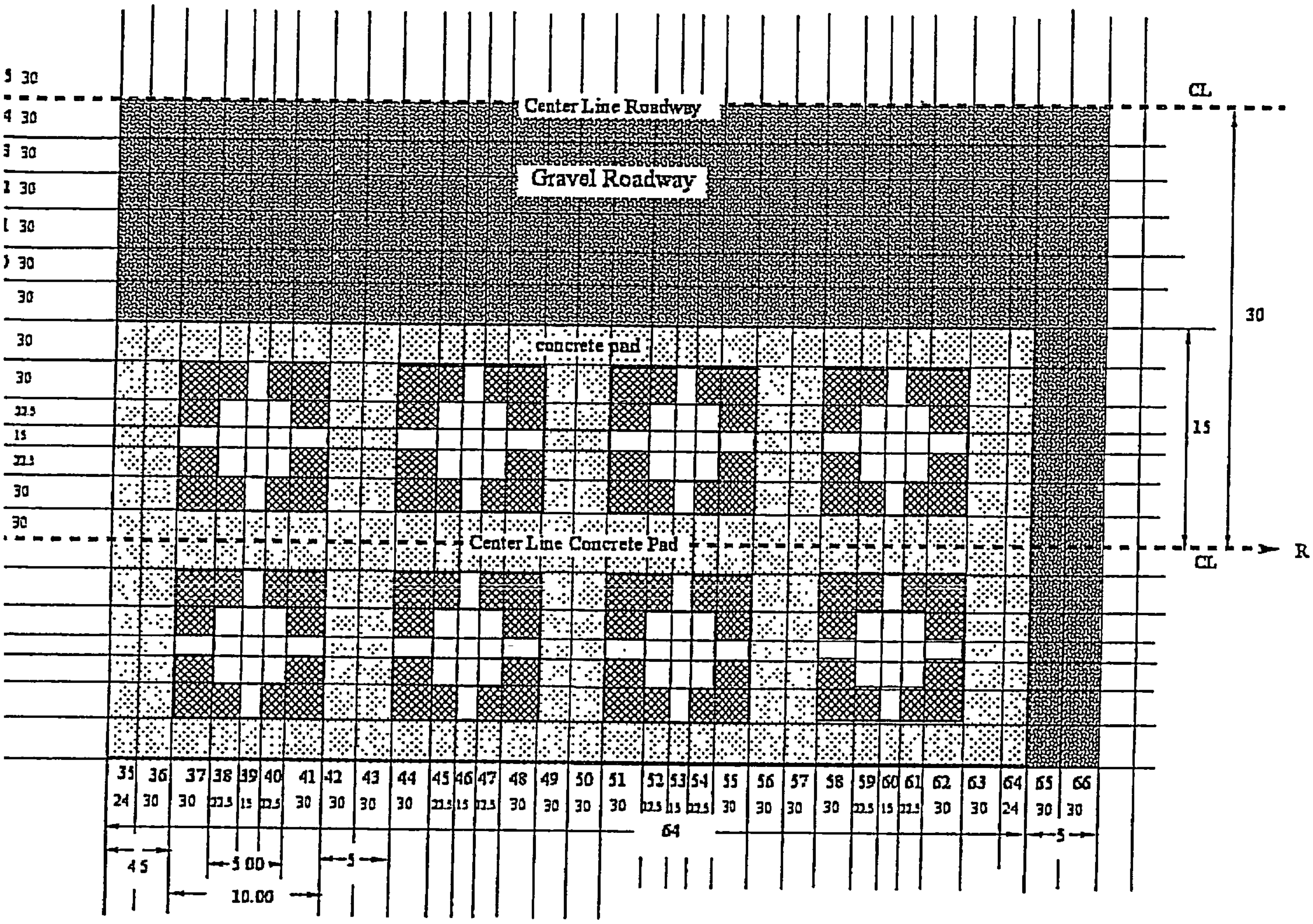
1/2 Assembly Rod node Map
For COBRA-SFS Model



TEMPEST Vertical grid structure: cell numbers and thicknesses
Not to Scale

Pad # 1


Center Line Roadway
Gravel Roadway
concrete pad
Center Line Concrete Pad
CL
CL
30
15
64
4.5
5.00
10.00
5
5



Center Line Roadway
CL
Gravel Roadway
concrete pad
Center Line Concrete Pad
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45
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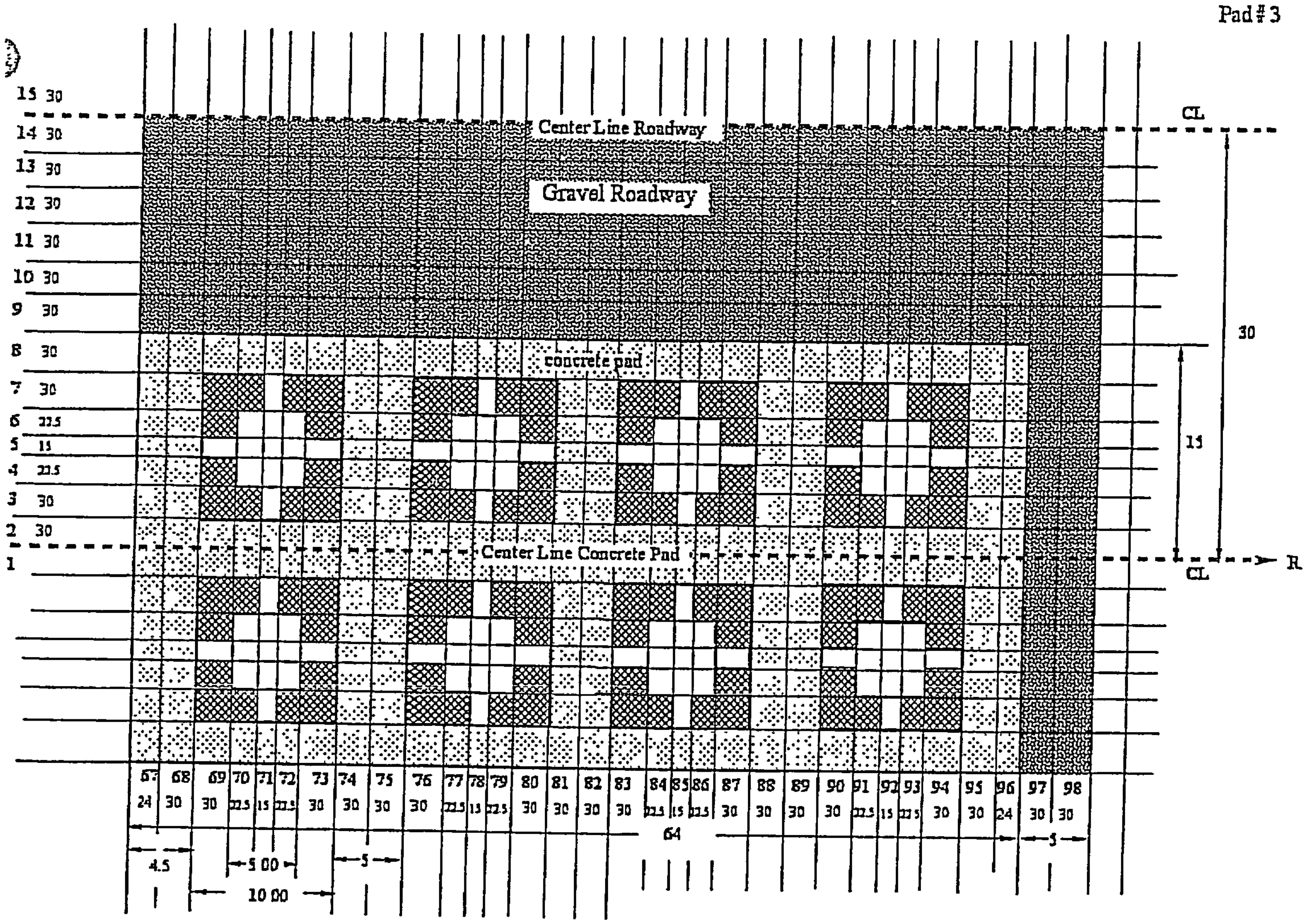
15 30
14 30
13 30
12 30
11 30
10 30
9 30
8 30
7 30
6 22.5
5 15
4 22.5
3 30
2 30
1
Center Line Roadway
Gravel Roadway
concrete pad
Center Line Concrete Pad
CL
CL
R
30
15
67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98
24 30 30 22.5 15 22.5 30 30 30 30 22.5 15 22.5 30 30 30 30 22.5 15 22.5 30 30 30 30 22.5 15 22.5 30 30 24 30 30
4.5
5.00
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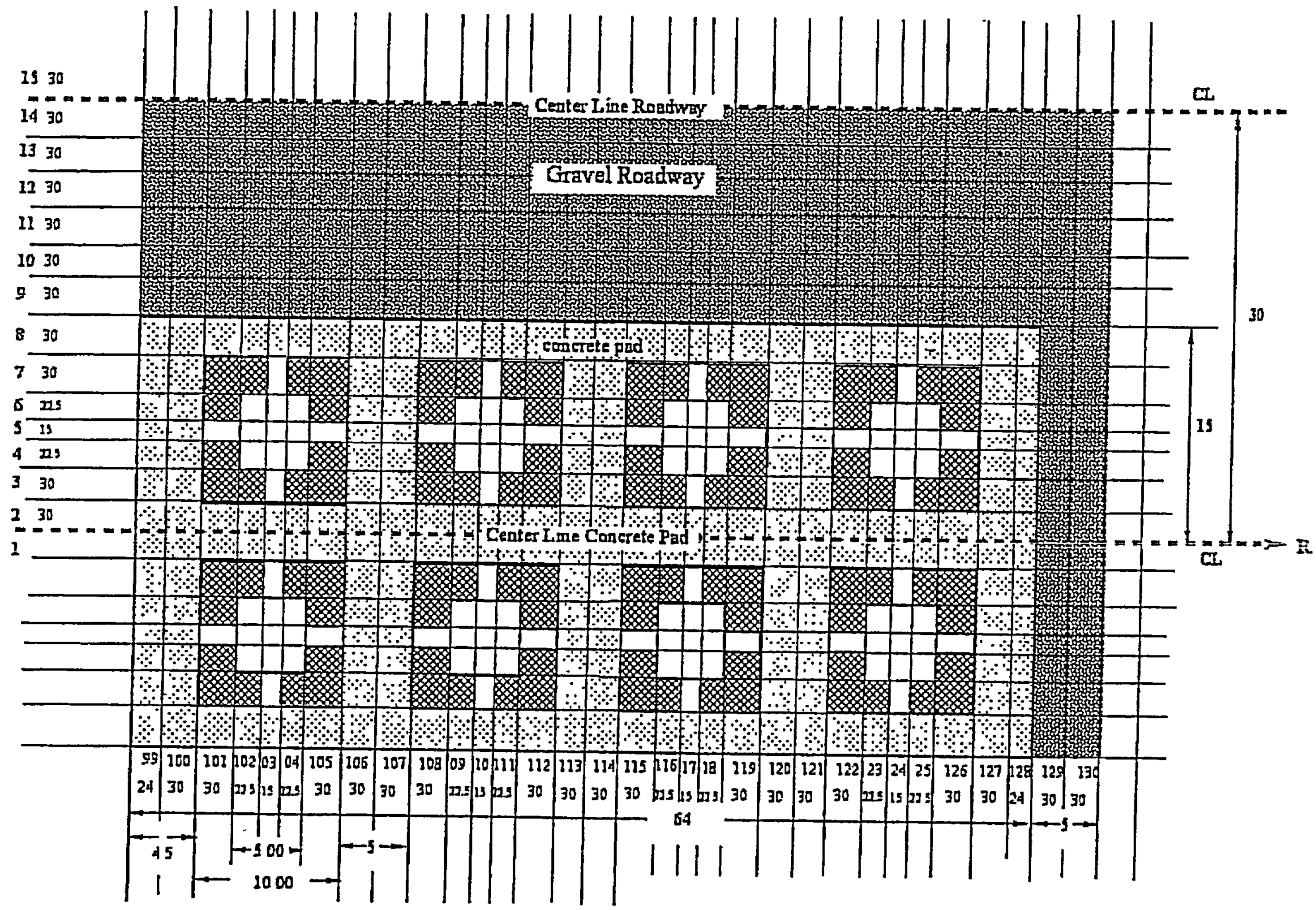
5


Center Line Roadway
CL
Gravel Roadway
concrete pad
Center Line Concrete Pad
CL
R
30
15
64
4 5
5 00
10 00
5

Pad # 5
last
pad