UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

Before the Atomic Safety and Licensing Board

In the Matter of	)	
	)	
PRIVATE FUEL STORAGE L.L.C.	)	Docket No. 72-22
	)	
(Private Fuel Storage Facility)	)	

AFFIDAVIT OF KRISHNA SINGH

CITY OF MARLTON	)
	) SS:
STATE OF NEW JERSEY	)

Krishna P. Singh, being duly sworn, states as follows:

1. I am President and CEO of Holtec International. In that position I bear the ultimate corporate responsibility for the accuracy and correctness of the company's spent fuel storage systems engineered for dry storage under certification by the USNRC. I am providing this affidavit in support of a motion for partial summary disposition of Contention Utah K in the above captioned proceeding to describe the ability of the Holtec HI-STORM 100 spent fuel storage cask, to be used at the Private Fuel Storage Facility (PFSF), to withstand heat and temperatures under fire conditions.

2. My professional and educational experience is summarized in the curriculum vitae attached as Exhibit 1 to this affidavit. My professional experience in spent fuel system design extends to 1979. Over the past twenty years, I have personally led the design and licensing of spent fuel storage systems for over forty nuclear plants, and for Holtec's HI-STAR 100 and HI-STORM 100 Systems. I am also the inventor of the honeycomb basket design utilized in the HI-STAR 100/HI-STORM 100 MPC Systems (Patent Number 5,898,747). The internal thermosiphon feature of the HI-STORM 100 MPCs, widely recognized as a seminal

contribution to dry storage technology, was conceptualized and implemented under my technical leadership. My professional work in the field of applied heat transfer, to which this affidavit pertains, consists of over 500 industry reports, over fifty published papers in the refereed technical literature, and academic courses taught at the University of Pennsylvania. I have served as the expert witness in two prior ASLB hearings dealing with wet storage of spent nuclear fuel.

3. I participated in, and am knowledgeable regarding, the thermal design of the Holtec HI-STORM 100 spent fuel storage cask, in particular its capability to withstand heat and temperatures under fire conditions. Specifically, the Holtec HI-STORM 100 storage casks, to be used at the PFSF, are designed to withstand a fire induced temperature of 1475 °F for at least 15 minutes, as described in the Topical Safety Analysis Report (TSAR, Revision 4) for the HI-STORM 100, at section 11.2.4 (attached as Exhibit 2). The design capability of the HI-STORM 100 to withstand a fire-induced temperature of 1475 °F for at least 15 minutes is also summarized in the PFSF SAR at 8.2-26.

4. The HI-STORM 100 spent fuel storage cask system consists of a sealed, cylindrical, steel multipurpose canister (containing the spent fuel assemblies and pressurized helium gas) standing on end inside a ventilated, steel-encased, cylindrical concrete storage overpack. The cask is 239.5 in. high and 132.5 in. in diameter. The concrete overpack is 29.5 inches thick. The HI-STORM 100 is depicted in the PFSF SAR in Figure 4.2-1.

5. As described in section 11.2.4 of the HI-STORM 100 SAR, Holtec analyzed the effect of fire on the HI-STORM 100 storage cask using the ANSYS finite element heat transfer code. The use of this code for the thermal analysis of spent fuel dry cask storage systems is recommended by NUREG-1536, Standard Review Plan for Dry Cask Storage Systems. NUREG-1536 at 4-7. The code models both conductive and radiative heat transfer between the structural elements of the cask system and the spent fuel as well as convective and radiative heat transfer between the cask surface and the environment.

6. In analyzing the fire, Holtec assumed that the storage cask was subjected to an ambient air temperature of 1475 °F for 15 minutes. The analysis showed that exposing the storage cask to an ambient air temperature of 1475 °F for this period of time would not cause the spent fuel or the fuel canister to exceed their design temperatures. The temperature increase of

the spent fuel would be negligible, and both the spent fuel and the fuel canister would be well within their design limits (HI-STORM 100 SAR at 11.2-12). Furthermore, while such temperature exposure might cause the concrete within a very small radial extent near the outer cylindrical surface of the cask to lose some neutron shielding capability, the great majority of the 29.5 inch thick concrete cask would experience only relatively minor temperature increases (due to the low concrete thermal conductivity) which would not adversely affect its neutron shielding capability. See Exhibit 2, HI-STORM 100 SAR Figures 11.2.1 to 11.2.5 (concrete temperature profiles as functions of time). Thus, the storage cask would continue to fully meet NRC regulatory requirements.

7. The potential for a Holtec HI-STORM 100 spent fuel storage cask to be damaged by the heat from a fire depends on the total amount of energy absorbed by the cask from the fire. A fire that produced a maximum air temperature at the surface of a storage cask of 1475 °F, or less, for a period of 15 minutes, or less, would in no way threaten the integrity of the casks or the spent fuel inside them.

K P Singh
Dr. Krishna P. Singh

Sworn to before me this 4th day of June 1999.

Maria C. Pepe
Notary Public

MARIA C. PEPE
NOTARY PUBLIC OF NEW JERSEY
My Commission Expires April 25, 2000

My Commission expires ____________________

EXHIBIT 1

RESUME OF DR. KRISHNA P. SINGH

RESUME

KRISHNA P. SINGH, Ph.D.
PRESIDENT & CEO

EDUCATION

University of Pennsylvania
Ph.D. in Mechanical Engineering (1972)

University of Pennsylvania
M.S. in Mechanical Engineering (1969)

B.I.T. Sindri, Ranchi University
B.S. In Mechanical Engineering (1967)

PROFESSIONAL EXPERIENCE

HOLTEC INTERNATIONAL
Marlton, New Jersey

1986 - Present President and CEO

JOSEPH OAT CORPORATION
Camden, New Jersey

1979 - 1986	Vice President of Engineering
1974 - 1979	Chief Engineer
1971 - 1974	Principal Engineer

R.I.T. ALLAHABAD
India

1967 - 1968	Assistant Professor of Applied Mechanics

LICENSES

Registered Professional Engineer - Pennsylvania (1974 - present)

Registered Professional Engineer - Michigan (1980 - present)

PROFESSIONAL MEMBERSHIPS/ACTIVITIES

Fellow of the ASME; Member ANS; Chairman, TEMA Vibration Committee (1979 - 1986); Chairman, PVP Committee Of the ASME, Nuclear Engineering Division (1988-92); Member, ASME O&M Committee (1991 to present); Member ASCE (1977-83), Member, Heat Exchange Institute (1976-86).

PATENTS

"Heat Exchanger for Withstanding Cycle Changes in Temperature" (with M. Holtz and A. Soler), Patent No. 4,207,944 (1980).

"Radioactive Fuel Cell Storage Rack" (with M. Holtz), U.S. Patent No. 4,382,060 (May, 1983).

BOOKS AND ARCHIVAL VOLUMES (authored or edited):

1. "Mechanical Design of Heat Exchangers and Pressure Vessel Components", (with A. I. Soler), Arcturus Publishers, Cherry Hill, New Jersey, 1100 pages, hardbound (1984).

2. "Theory and Practice of Heat Exchanger Design", Arcturus Publishers (c. 1995).

3. "Feedwater Heater Workshop Proceedings", with Tom Libs, EPRI 78-123 (1979).

4. "Feedwater Heater Technology: State-of-the-Art", EPRI - cs - 4155 (1985).

5. "Analytical Correlations of Fluid Drag of Fuel Drag of Fuel Assemblies in Fuel Rack Storage Locations", EPRI Project RP-2124.

6. "Thermal/Mechanical Heat Exchanger Design", ASME, PVP - Vol. 118 (1986).

7. "Time Dependent and Steady State Characterization of the CAES Recuperator", EPRI TR-104224 (July 1994).

8. "Pressure Vessels, Heat Exchangers and Piping", Proc. ASME, IEEE Joint Power Generation Conference, NE-14 (1994).

EXPERT WITNESS AND TECHNOLOGY APPRAISAL SERVICES

1. Pacific Gas & Electric Company vs. National Sierra Club (1986-87).

2. Florida Power & Light Company vs. Stuart Intervenor Group (1990).

3. Duquesne Light Company vs. Westinghouse (1993-).

4. Portland General Electric vs. Westinghouse (1993-).

5. Houston Light and Power (1994-).

6. Pacific Northwest Laboratories, Rockwell International, and U.S. DOE vs. RSI (1994-).

ACADEMIC ACTIVITIES

Chair, Advisory Committee On Mechanical Engineering and Mechanics, University of Pennsylvania (1993-)

Professor (Adjunct) in Mechanical Engineering and Mechanics, University of Pennsylvania (1986-92), Graduate and Undergraduate Courses in Heat Transfer Equipment

CONTINUING EDUCATION COURSES OFFERED ON HEAT EXCHANGE AND STEAM GENERATION

1. I.I.T. Bombay, One Week Course on Heat Exchanger Design (1979).

2. Duke Power Company, Charlotte, NC (1982, 1983, 1986, 1990) - In-house Course on Heat Exchanger Design and Testing.

3. National Italian Reactor Authority, Genoa, Italy - On Condensers, Steam Generators, and Moisture Separator Reheaters (1985).

4. Mississippi Power & Light Company, In-House Course on Moisture Separator Reheaters and Surface Condensers (1987).

5. Center for Professional Advancement (1988, New Brunswick, NJ; 1990, Caracas, Venezuela; 1991, Houston, Texas; 1992, Amsterdam, Holland).

CONSULTING

Consultant to Electric Power Research Institute (EPRI); Pressure Vessel Research Council (PVRC); Tubular Exchanger Manufacturers Association (TEMA); Department of Energy (DOE) (Idaho Operations); Department of Energy (DOE) (Chicago Operations); American Electric Power Corporation; Baltimore Gas and Electric; Carolina Power & Light; Commonwealth Edison Company; Detroit Edison Company; Duke Power Company; Entergy Operations; GPU Nuclear; Iowa Electric Light and Power; New York Power Authority; Niagara Mohawk Power Corporation; North Atlantic Energy Services; Northeast Utilities; Northeast Nuclear Energy; Pacific Gas and Electric Company; PECO Energy; Southern Nuclear Operating Company; Tennessee Valley Authority.

PUBLICATIONS

1. "A Method for Solving Ill-Posed Integral Equations of the First Kind", (with B. Paul), Computer Methods in Applied Mechanics and Engineering 2 (1973) 339-348.

2. "Numerical Solutions of Non-Hertzian Elastic Contact Problems", (with B. Paul), Journal of Applied Mechanics, Vol. 41, No. 2, 484-490, June, 1974.

3. "On the Inadequacy of Hertzian Solution of Two Dimensional Line Contact Problems", Journal of the Franklin Institute, Vol, 298, No. 2, 139-141 (1974).

4. "How to Locate Impingement Plates in Tubular Heat Exchangers", Hydrocarbon Processing, Vol. 10, 147-149 (1974).

5. "Stress Concentration in Crowned Rollers", (with B. Paul), Journal of Engineering for Industry, Trans. ASME, Vol. 97, Series B, No. 3, 990-994 (1975).

6. "Application of Spiral Wound Gaskets for Leak Tight Joints", Journal of Pressure Vessel Technology, Trans. ASME, Vol. 97, Series J, No. 1, 91-93 (1975).

7. "Contact Stresses for Multiply-Connected Regions - The Case of Pitted Spheres:, with B. Paul and W. S. Woodward, Proceedings of the IUTAM Symposium on Contact Stresses, August 1974, Holland, Delft University Press, 264-281, (1976).

8. "Design of Skirt-Mounted Supports:, Hydrocarbon Processing, Vol. 4, 199-203, April 1976.

9. "Predicting Flow Induced Vibration in U-Bend Regions of Heat Exchangers - An Engineering Solution". Journal of the Franklin Institute, Vol. 302, No. 2, 195-205, August 1976.

10. "A Method to Design Shell-side Pressure Drop Constrained Tubular Heat Exchangers", with Mr. Holtz, Journal of Engineering for Power, Trans. of the ASME, Vol. 99, No. 3 July 1977, pp 441-448.

11. "An Efficient Design Method for Obround Pressure Vessels and Their End Closures", International Journal of Pressure Vessel and Piping, Vol. 5, 1977, pp 309-320.

12. "Analysis of Vertically mounted Through-Tube Heat Exchangers", Journal of Engineering for Power, Trans. ASME, Vol. 100, No. 2, April, 1978, pp 380-390.

13. "Study of Bolted Joint Integrity and Inter-Tube-Pass Leakage in U-Tube Heat Exchangers: Part I - Analysis", Journal of Engineering for Power, Trans. ASME, Vol. 101, No. 1, pp 9-15 (1979).

14. "Study of bolted Joint Integrity and Inter-Tube-Pass Leakage in U-Tube Heat Exchangers, Part II - Applications", Journal of Engineering for Power, Trans. ASME, Vol. 101, No. 1, pp 16-22 (1979).

15. "On Thermal Expansion Induced Stresses in U-Bends of Shell-and-Tube Heat Exchangers", (with Maurice Holtz); Trans. ASME, Journal of Engineering for Power, Vol. 101, No. 4, October, 1979, pp. 634-639.

16. "Heat Transfer Characteristics of a Generalized Divided Flow Heat Exchanger", Proceedings of the Conference on Industrial Energy Conservation Technology, Houston, Texas, pp 88-97 (1979).

17. "An Approximate Analysis of Foundation Stresses in Horizontal Pressure Vessels", (with Vincent Luk), Paper No. 79-NE-1, Trans. ASME, Journal of Engineering for Power, Vol. 102, No. 3, pp 555-557, July, 1980.

18. "Generalization of the Split Flow Heat Exchanger Geometry for Enhanced Heat Transfer", (with Michael Holtz), AIChe. Symposium Series 189, Vol. 75, pp 219-226 (1979).

19. "Analysis of Temperature Induced Stresses in the Body Bolts of Single Pass Heat Exchangers", ASME Winter Annual Meeting, Paper No. 79 QA/NE-7, New York, NY, 1979.

20. "Optimization of Two-Stage Evaporators for Minimizing Rad-Waste Entrainment", (with Maurice Holtz), Journal of Mechanical Design, Trans. of the ASME, Vol. 102, No. 4, pp 804-806 (1980).

21. "A Comparison of Thermal Performance of Two and Four Tube Pass Designs for Split Flow Shells", (with M. J. Holtz), Journal of Heat Transfer, Trans. of the ASME, Vol. 103, No. 1, pp 169-172, February, 1981.

22. "A Method for Maximizing Support Leg Stress in a Pressure Vessel Mounted on Four Legs Subject to Moment and Lateral Loadings". International Journal of Pressure Vessels and Piping, Vol. 9, No. 1, pp 11-25 (1981).

23. "Design, Stress Analysis and Operating Experience in Feedwater Heaters",, (with Tom Libs), Proceedings of the Conference on Industrial Energy Conservation Technology, Houston, pp 113-118 (1980).

24. "On the Necessary Criteria for Stream Symmetric Tubular Heat Exchanger Geometries", Heat Transfer Engineering, Vol. 3, No. 1 (1981).

25. "Some Fundamental Relationships for Tubular Heat Exchanger Thermal Performance", Trans. ASME, Journal of Heat Transfer, Vol. 103, pp 573-578 (1981).

26. "Transient Swelling of Liquid Level During Pool Boiling in an Emergency Condenser", (with J. P. Gupta). Letters in Heat and Mass Transfer, Vol. 8, No. 1, pp 25-33, Jan/Feb., 1981.

27. "An Approximate Method for Evaluating the Temperature Field in Tubesheet Ligaments Under Steady State Conditions", (with M. Holtz), Journal of Engineering for Power, Trans. ASME, Vol. 104, pp 895-900 (1982).

28. "Feasibility Study of A Multi-Purpose Computer Program to Optimize Power Cycles for Operative Plants", (with Y. Menuchin and N. Hirota), Proceedings of the Conference on Industrial Energy Conservation Technology, Houston, (1981).

29. "Design Parameters Affecting Bolt Load in Ring Type Gasketed Joints", (with A. I. Soler), Trans. ASME, Journal of Pressure Vessel Technology, Vol 105, pp 11-13 (1983).

30. "A Design Concept for Minimizing Tubesheet Stress and Tubejoint Load in Fixed Tubesheet Heat Exchangers", (with A. I. Soler), Trans. ASME (C. 1982).

31. "Dynamic Coupling in a Closely Spaced Two-Body System Vibrating in Liquid Medium: The Case of Fuel Racks", (with A. I. Soler), Proceedings of the Third International Conference on "Vibration in Nuclear Plant", Keswick, England, May, 1982, pp. 815-834.

32. "Effect of Nonuniform Inlet Air Flow on Air Cooled Heat Exchanger Performance", (with A. I. Soler and Lee Ng), Proceedings of the Joint ASME-JSME Heat Transfer Conference, 1983, pp. 537-542.

33. "Seismic Response of Free Standing Fuel Rack Constructions to 3-D Motions", (with A. I. Soler), Nuclear Engineering and Design, Vol. 80, (1984), pp. 315-329.

34. "A Method for Computing Maximum Water Temperature in a Fuel Pool Containing Spent Nuclear Fuel", Heat Transfer Engineering, Hemisphere, Dec. (1986).

35. "On Minimization of Radwaste Carry-Over in a N-stage Evaporator", (with Maurice Holtz and Vincent Luk), Heat Transfer Engineering, pp. 68-73, Vol. 5, No. 1-1 (1984).

36. "Feedwater Heater Procurement Guidelines - Some New Performance Criteria", Symposium on State-of-the-art Feedwater Heater Technology, EPRI (c. 1984).

37. "Method for Quantifying Heat Duty Derating due to Inter-Pass Leakage in Bolted Flat Cover Heat Exchangers", Heat Transfer Engineering, pp. 19-23, Vol. 4, No. 3-4 (1983).

38. "On Some Performance Parameters for Closed Feedwater Heaters, Journal of Pressure Vessel Technology, Trans. ASME (1987).

39. "A Design Procedure for Evaluating the Tube Axial Load Due to Thermal Effects in Multi-Pass Fixed Tubesheet Heat Exchangers", (with A. I. Soler), Journal of Pressure Vessel Technology, Trans. ASME (1987).

40. "An Elastic-Plastic Analysis of the Integral Tubesheet in U-Tube Heat Exchangers - Towards an ASME Code Oriented Approach", Int. Journal of Vessel and Piping (c. 1987).

41. "Feedwater Heaters", Heat Transfer Equipment Design, R. Shal et. al (editor), Hemisphere (c. 1988).

42. "Surface Condensers", Heat Transfer Equipment Design, R. Shal et. al (editor), Hemisphere (c. 1988).

43. "FLow Induced Vibration", Heat Transfer Equipment Design, R. Shal et. al (editor), Hemisphere (c. 1988).

44. "Mechanical Design of Heat Exchangers", Heat Transfer Equipment Design, R. Shal et. al (editor), Hemisphere (c. 1988).

45. "A Rational Method for Analyzing Expansion Joints":, (with A. Soler), ASME, Journal of Pressure Vessel Technology (c. 1988).

46. "An Analysis of the Improvement in the Thermal Performance of Surface Condenser Equipped with Tweener Supports", ASME Joint Power Generation Conference, Miami (Oct. 1987).

47. "Pressure Vessels - Design & Operation", Chemical Engineering, pp 62-70, Chemical Engineering, July 1990, McGraw Hill, N.Y.

48. "Spent Fuel Storage Options: A Critical Appraisal", Power Generation Technology, pp 137-140, Sterling Publications, U.K. (1990-91).

49. "Design Strength of Primary Structural Welds in Free-Standing Structures", with A.I. Soler and S. Bhattacharya, Journal of Pressure Vessel Technology, Trans. ASME (c' 1991).

50. "Seismic Qualification of Free-Standing Nuclear Fuel Storage Modules - The Chin Shan Experience", Nuclear Engineering International, U.K. (March, 1991).

51. "Transient Response of Large Inertia Cross Flow Heat Exchangers", with Y. Wang, A.I. Soler and K. Iulianetti, ASME 91-JPGC-NE-27 (1991).

52. "Some Results from Simultaneous Seismic Simulations of All Racks in a Fuel Pool", with A.I. Soler, INNM Spent Fuel Management Seminar X, Washington, D.C., January, 1993.

53. "A Case for Wet Storage", INNM Spent Fuel Management Seminar X, Washington, D.C., January, 1993.

54. "Application of Transient Analysis Methodology to Heat Exchanger Performance Testing" with I. Rampall and Benjamin H. Scott, ASME Joint Power Generation Conference, October, 1994.

55. "Predicting Thermal Performance of Heat Exchangers Using In-Situ Testing and Statistical Correlation", with K. Iulianetti and Benjamin H. Scott, ASME Joint Power Generation Conference (1994).

56. "Shellside Boiling in Narrow Crevices", with I. Rampall (to be submitted for publication, Heat Transfer Engineering (ca. 1996)).

EXHIBIT 2

(EXTRACTED FROM REVISION 4 OF THE HI-STORM TSAR
DATED MAY 1998)

(Exhibit 2 contains twelve pages)

11.2.4 Fire Accident

11.2.4.1 Cause of Fire

Although the probability of a fire accident effecting a HI-STORM 100 System during storage operations is low due to the lack of combustible materials at the ISFSI, a conservative fire has been assumed and analyzed. The analysis shows that the HI-STORM 100 System continues to perform its structural, confinement, thermal, and subcriticality functions.

11.2.4.2 Fire Analysis

11.2.4.2.1 Fire Analysis for HI-STORM Overpack

The possibility of a fire accident near an ISFSI is considered to be extremely remote due to an absence of combustible materials within the ISFSI and adjacent to the overpacks. The only credible concern is related to a transport vehicle fuel tank fire, causing the outer layers of the storage overpack to be heated by the incident thermal radiation and convective heat fluxes.

The amount of combustible fuel in the transporter is limited to a volume of 200 gallons based on a Technical Specification in Section 12.3. Based upon results of large pool burning rate experiments [11.2.2], it is conservatively postulated that any transport vehicle fire results in a 1475°F fire environment, and that the fuel burns at a rate of 0.15 inches per minute. Based on IAEA Safety Standards [11.2.3], it is conservatively postulated that a ring of fuel with a width of one meter, a surface area of 21,260 in^2, and a depth of 2.17 in. forms around the storage overpack. Based on these conservative parameters, the maximum duration of the fire is bounded by a time of 15 minutes, during which all outer surfaces of the HI-STORM overpack are exposed to incident radiative and convective heat fluxes.

The inner surface of the overpack is conservatively assumed to be insulated. Because of the severity of the fire condition radiative heat flux, heat flux from incident solar radiation is negligible and is not included. Furthermore, the smoke plume from the fire would block most of the solar radiation. The thermal transient response of the storage overpack is determined using the ANSYS finite element program. Time-histories for points in the storage overpack were monitored for the duration of the fire and the subsequent post-fire equilibrium phase.

Heat input to the HI-STORM overpack while it is subjected to the fire is from a combination of an incident radiation and convective heat fluxes to all external surfaces. This can be expressed by the following equation:

$$q_F = h_{fc}(T_A - T_S) + 0.1714\times10^{-8}\epsilon[(T_A+460)^4 - (T_S+460)^4]$$

where:

q_F = Surface Heat Input Flux (Btu/ft^2-hr)
h_{fc} = Surface Heat Transfer Coefficient (Btu/ft^2-hr-°F)
T_A = Fire Condition Temperature (1475°F)
T_S = Transient Surface Temperature (°F)
ϵ = Surface Emissivity = 0.85 (flame emissivity = 1.0)

The forced convection heat transfer coefficient is calculated to bound the convective heat flux contribution to the exposed cask surfaces due to fire induced air flow. For the case of air flow past a heated cylinder, Jacob [11.2.4] recommends the following correlation for convective heat transfer obtained from experimental data:

$$Nu_{fc} = 0.028\ Re^{0.8}\ [\ 1 + 0.4\ (\frac{L_{st}}{L_{tot}})^{2.75}\ ]$$

where:

L_{tot} =	length traversed by flow
L_{st} =	length of unheated section
K_f =	thermal conductivity of air evaluated at the average film temperature
Re =	flow Reynolds Number based on L_{tot}
Nu_{fc} =	Nusselt Number ($h_{fc}\ L_{tot}/K_f$)

A consideration of the wide range of temperatures to which the exposed surfaces are subjected to during the fire and the temperature dependent trend of air properties requires a careful selection of parameters to determine a conservatively large bounding value of the convective heat transfer coefficient. In Table 11.2.1, a summary of parameter selections with justifications provide an appropriate basis for application of this correlation to determine forced convection heating of the overpack during a short-term fire event.

After the 15 minute fire event, the ambient temperature is restored to 80°F and the storage overpack cools down (post-fire equilibrium). Heat loss from the outer surfaces of the storage overpack is determined by the following equation:

$$q_S = h_S(T_S - T_A) + 0.1714\times10^{-8}\epsilon[(T_S+460)^4 - (T_A+460)^4]$$

where:

q_S = Surface Heat Loss Flux (Btu/ft^2-hr)
h_S = Surface Heat Transfer Coefficient (Btu/ft^2-hr-°F)
T_S = Transient Surface Temperature (°F)
T_A = Ambient Temperature (°F)
ϵ = Surface Emissivity

In the post-fire equilibrium phase, the surface heat transfer coefficient (h_S) is determined by the following equation:

$$h_S = 0.19 \times |T_A - T_S|^{1/3}$$

where:

h_S = Surface Heat Transfer Coefficient (Btu/ft^2-hr-°F)
T_A = External Air Temperature [Fire or Ambient] (°F)
T_S = Surface Temperature (°F)

A two-dimensional, axisymmetric model was developed for this analysis. Concrete thermal properties used were taken from Section 4.2. The ANSYS model with temperature monitoring locations is shown in Figure 11.2.1. The outer surface and top surface of the overpack are exposed to the ambient conditions (fire and post-fire). The base and the inner surface of the overpack are insulated. The transient study is conducted for a period of 10 hours, which is sufficient to allow all temperatures in the overpack to reach their maximum values and begin to recede.

Based on the results of the analysis, the maximum temperature increases at several points near the overpack mid-height are summarized in Table 11.2.2 along with the corresponding peak temperatures. Temperature profiles through the storage overpack wall thickness near the mid-height of the cask are included in Figures 11.2.2 through 11.2.4. A plot of temperature versus time is shown in Figure 11.2.5 for several points through the overpack wall, near the mid-height of the cask. The temperature profile plots (Figures 11.2.2 through 11.2.4) each contain profiles corresponding to time "snapshots". Profiles are presented at the following times: 15 minutes, 30 minutes, 1 hour, 2 hours, 4 hours, 7 hours, and 10 hours.

The primary shielding material in the storage overpack is concrete, which can suffer a reduction in neutron shielding capability at sustained high temperatures. The results of the analysis show that the intense heat from the fire only partially penetrates the overpack wall, and that the majority of the concrete experiences a relatively minor temperature increase. The concrete that is exposed to extreme temperatures could experience a minor reduction of neutron shielding capability.

Examining Table 11.2.2, it is seen that the overpack inner shell temperature is relatively unaffected by the fire. From this result it can be concluded that a negligible amount of heat for the fire reaches the MPC. Therefore, the temperature of the MPC is increased by the contained decay heat only. Given the large mass of a loaded MPC and the short duration of the fire, the temperature rise of the MPC and stored fuel will be small and a large margin to the short-term cladding temperature limits will exist. Consequently, the impact on the MPC internal helium pressure is expected to be negligibly small. Based on a conservative analysis of the HI-STORM 100 System response to a hypothetical fire event, it is concluded that the fire event does not significantly affect the temperature of the MPC. Furthermore, the ability of the HI-STORM 100 System to cool the spent nuclear fuel within design temperature limits during post-fire equilibrium is not compromised.

Structural

As discussed above, there are no structural consequences as a result of the fire accident condition.

Thermal

As discussed above, the MPC internal pressure increases a negligible amount and is bounded by the 100% fuel rod rupture accident in Section 11.2.9. As shown in Table 11.2.2, the peak fuel cladding and material temperatures are well below short-term accident condition allowable temperatures of Table 2.2.3.

Shielding

There is a limited effect on the shielding performance of the system as a result of this event, since the concrete bulk temperature does not exceed its normal design condition temperature of 300°F.

Criticality

There is no effect on the criticality control features of the system as a result of this event.

Confinement

There is no effect on the confinement function of the MPC as a result of this event.

Radiation Protection

Since there is limited degradation in shielding on the overpack exterior surface and no degradation of confinement capabilities as discussed above, there is a negligible effect on occupational or public exposures as a result of this event.

Based on this evaluation, it is concluded that the overpack fire accident does not affect the safe operation of the HI-STORM 100 System.

11.2.4.2.2 Fire Analysis for HI-TRAC Transfer Cask

To demonstrate the fuel cladding and MPC pressure boundary integrity under an exposure to a hypothetical short duration fire event during on-site handling operations, a fire accident analysis of the loaded 100-ton HI-TRAC is performed. This analysis, because of the lower mass of 100-ton HI-TRAC, bounds the effects for the 125-ton HI-TRAC. In this analysis, the contents of the HI-TRAC are conservatively postulated to undergo a transient heat up as a lumped mass from the decay heat input and heat input from the short duration fire. The rate of temperature rise of the HI-TRAC depends on the thermal inertia of the cask, the cask initial conditions, the spent nuclear fuel decay heat generation, and the fire heat flux. All of these parameters are conservatively bounded by the values in Table 11.2.3 which are used for the fire transient analysis.

Using the values stated in Table 11.2.3, a bounding cask temperature rise of less than 9°F per minute is determined from the combined radiant and convection fire and decay heat inputs to the cask. During the handling of the HI-TRAC transfer cask, the transporter is limited to a maximum of 50 gallons, in accordance with a Technical Specification in Section 12.3. The duration of the 50 gallon fire is less than 5 minutes. Therefore, the fuel cladding will not exceed the short term fuel cladding temperature limit (see Table 11.2.5).

The elevated temperatures as a result of the fire accident will cause the pressure in the water jacket to increase and cause the overpressure relief valve to vent steam to the atmosphere. It is conservatively assumed, for dose calculations, that all the water in the water jacket is lost.

Due to the increased temperatures the MPC experiences as a result of the fire accident in the HI-TRAC transfer cask, the MPC internal pressure increases. Table 11.2.4 provides the MPC maximum internal pressures as a result of the HI-TRAC fire accident. Table 11.2.5 provides a summary of the loaded HI-TRAC bounding maximum temperatures for the hypothetical fire accident condition.

Table 11.2.1

SUMMARY OF TEMPERATURE-DEPENDENT FORCED CONVECTION HEAT TRANSFER CORRELATION PARAMETERS FOR AIR

Parameter	**Trend with Increasing Temperatures**	**Criteria to Maximize h_{fc}**	**Conservative Parameter Value**	**Evaluated At**
Temperature Range	100°F-1475°F	NA	NA	NA
Density	Decreases	Reynolds Number	High	100°F
Viscosity	Increases	Reynolds Number	Low	100°F
Conductivity (K_f)	Increases	h_{fc} Proportional to K_f	High	1475°F

Table 11.2.2

HI-STORM 100 OVERPACK TEMPERATURES AS A RESULT OF THE HYPOTHETICAL FIRE CONDITION

Material/Component	Initial† Condition (°F)	During Fire (°F)	Post-Fire†† Cooldown (°F)
Overpack Inner Shell	200	200	208
Overpack Radial Concrete Inner Surface	200	200	208
Overpack Radial Concrete Mid-Surface	200	200	232
Overpack Outer Shell	200	1155	1155

† Bounding 200°F uniform temperature assumed (maximum normal condition calculated overpack component temperature = 165°F).

†† Maximum temperature during post-fire cooldown.

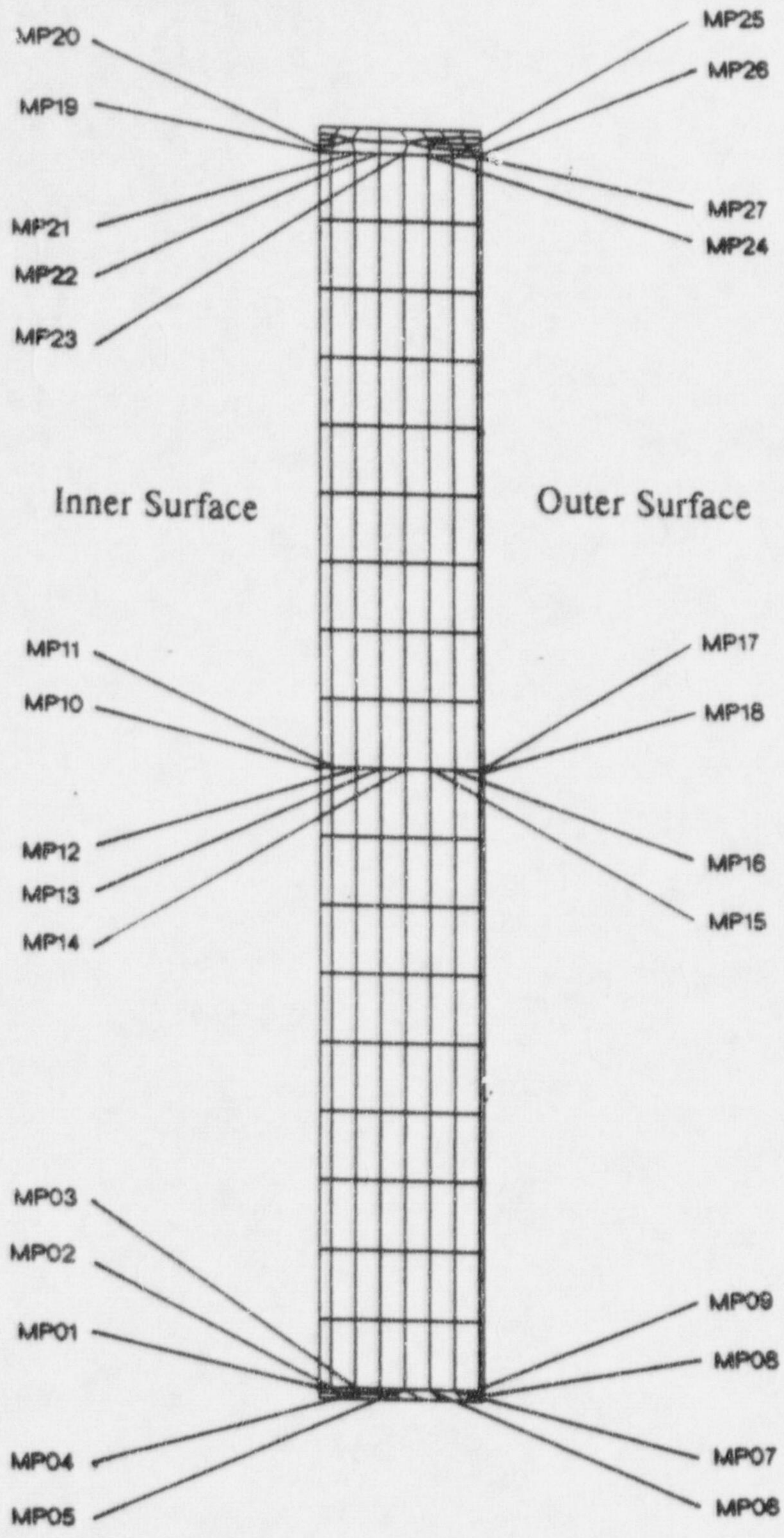

FIGURE 11.2.1; ANSYS MODEL AND TEMPERATURE MONITORING LOCATIONS

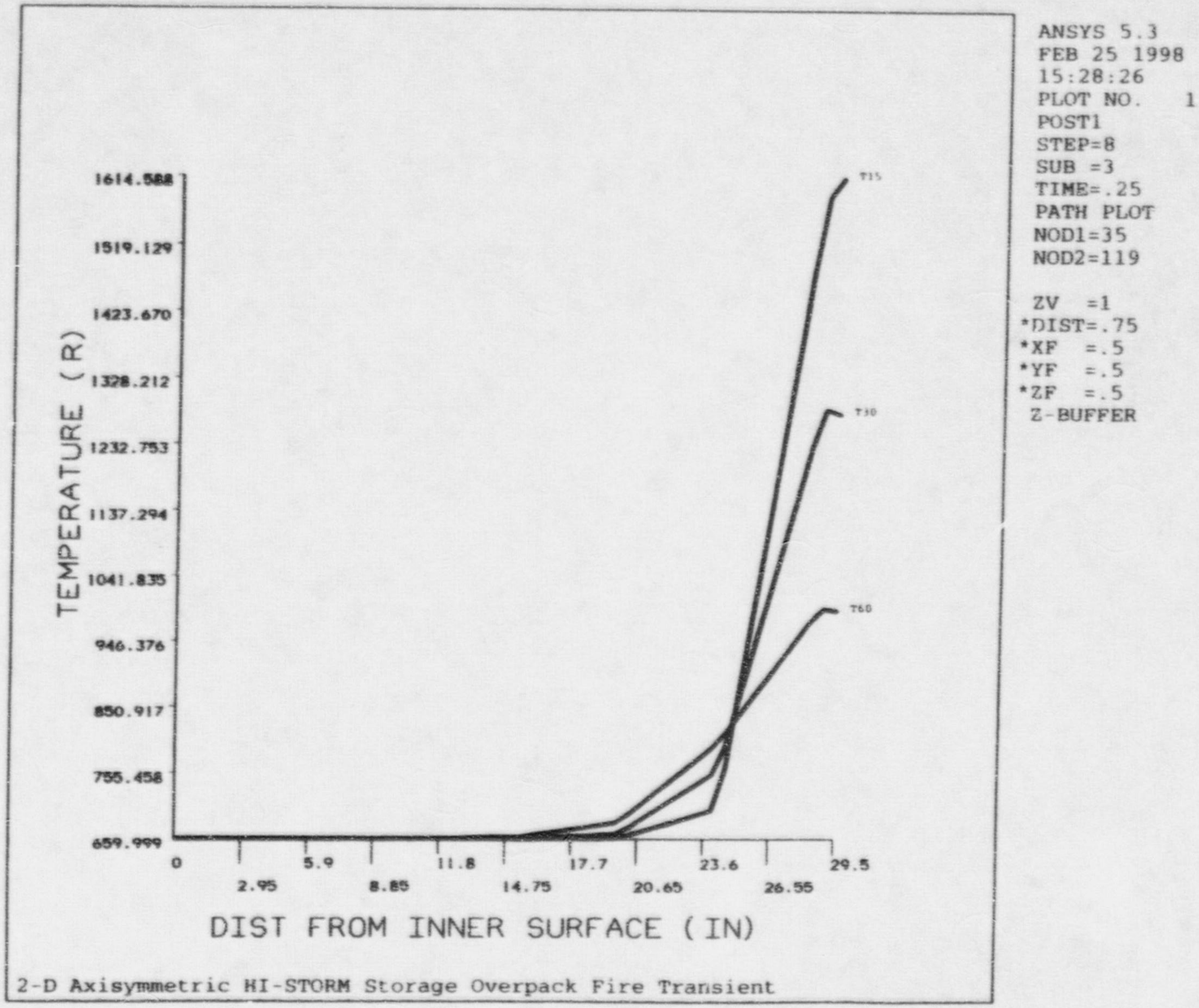

FIGURE 11.2.2; TEMPERATURE PROFILES THROUGH OVERPACK WALL AT 15, 30 AND 60 MINUTES

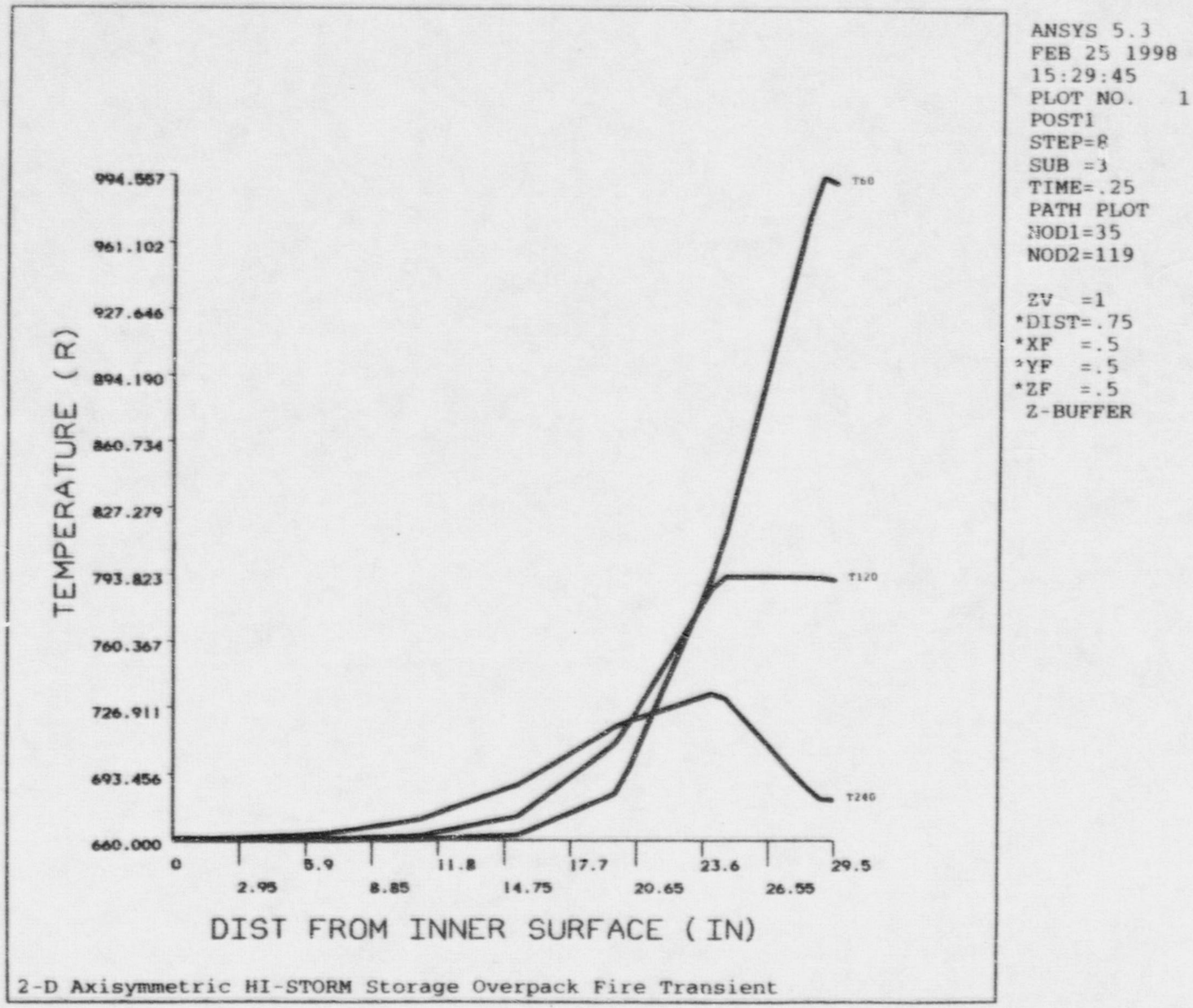

FIGURE 11.2.3; TEMPERATURE PROFILES THROUGH OVERPACK WALL AT 60, 120 AND 240 MINUTES

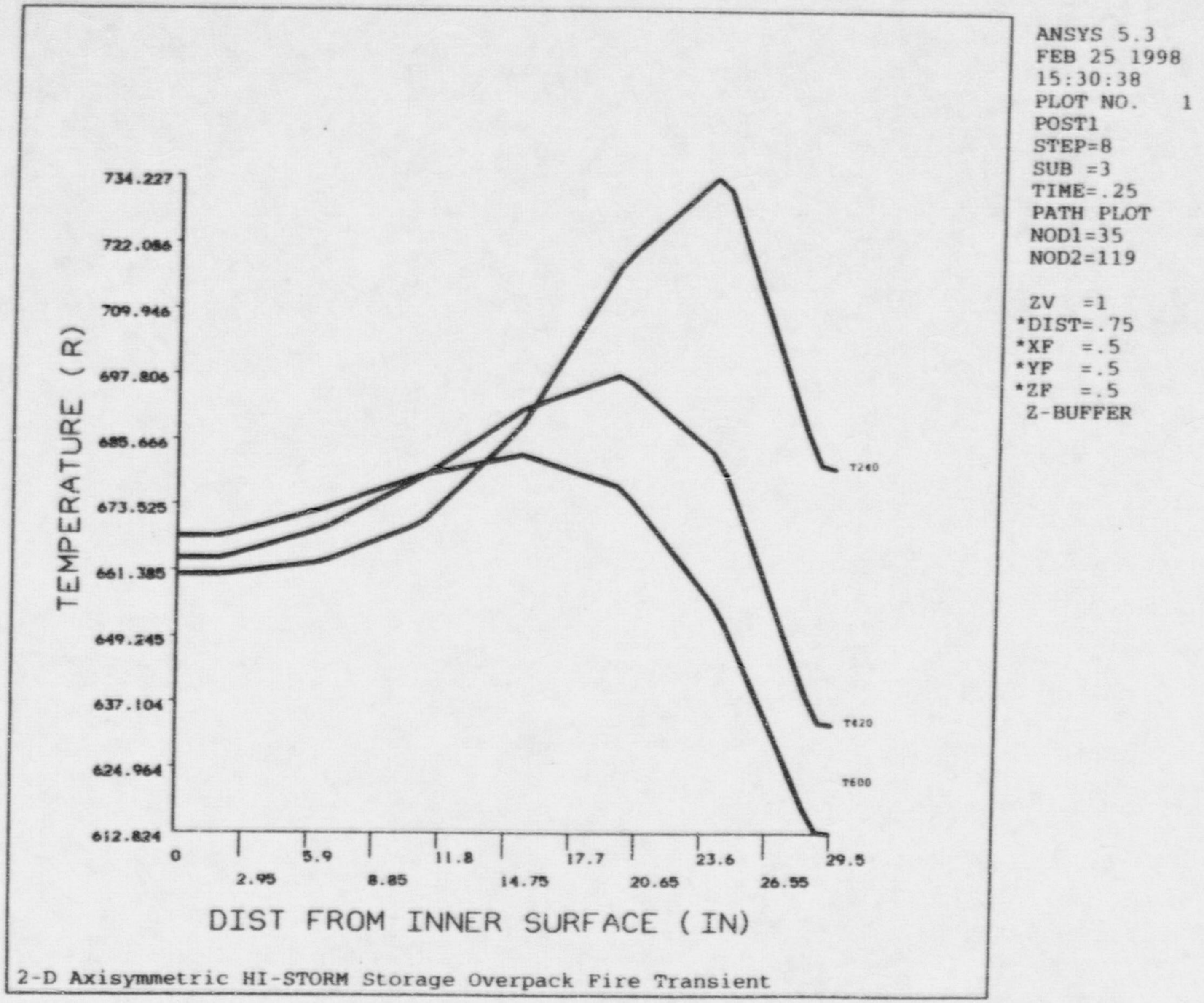

FIGURE 11.2.4; TEMPERATURE PROFILES THROUGH OVERPACK WALL AT 240, 420 AND 600 MINUTES

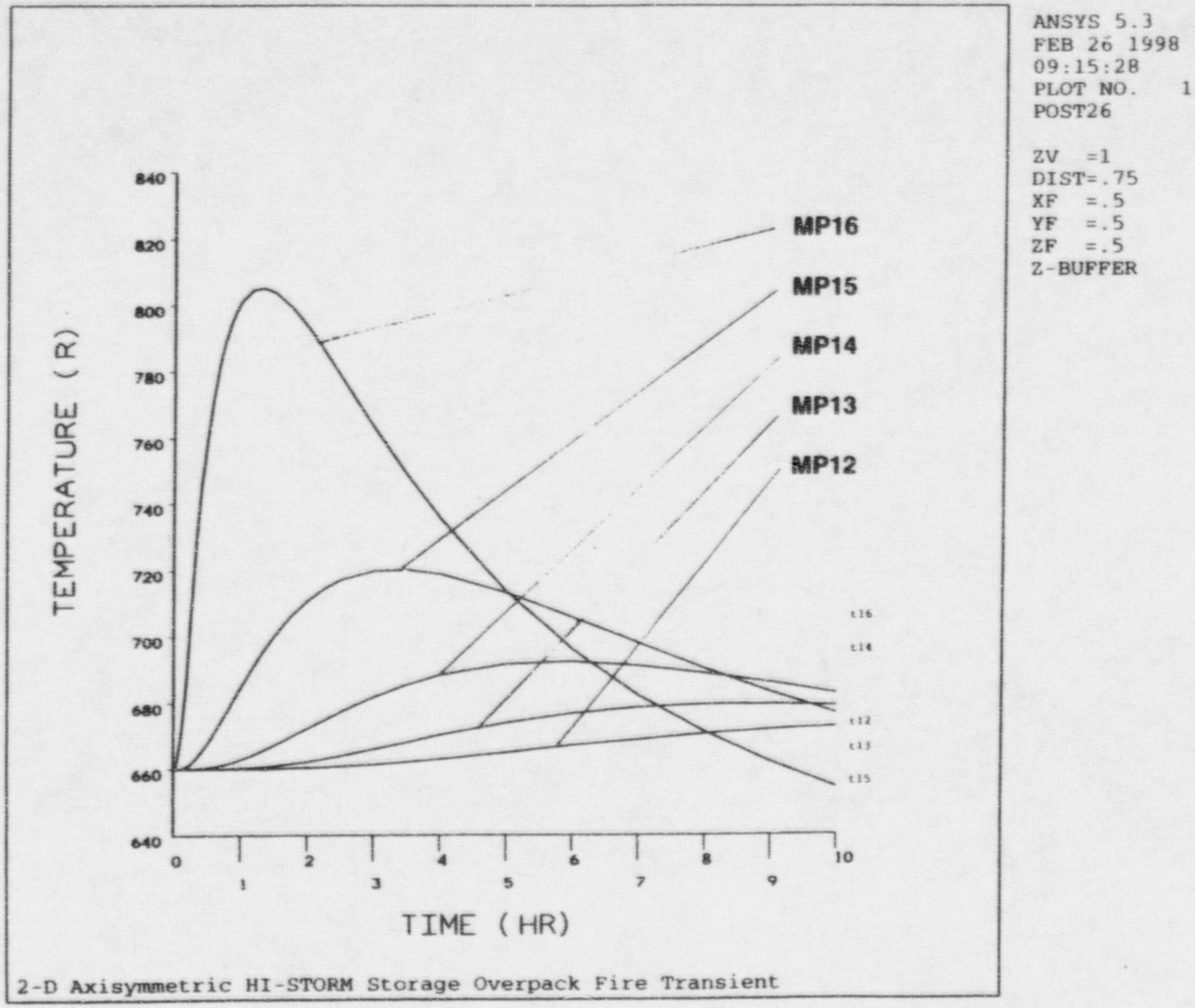

FIGURE 11.2.5; TEMPERATURE VS. TIME NEAR CASK MID-HEIGHT