NEW INSIGHTS INTO THE TEMPERATURE FIELDS IN SPENT FUEL POOLS: RECENT KOREAN EXPERIENCE

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ABSTRACT

High density storage racks(HDSRs) have been, and will continue to be installed in rerack campaigns to alleviate impending shortfall in spent fuel pool storage capacity at Kori-4 nuclear power plant in Korea and at other plants around the world. Truncation of sparger lines has become an effective strategy to increase storage capacity. Over a dozen spent fuel pools reracked in the past several years have removed their sparger lines to enable a high density storage layout and thus maximize pool capacity.

Sparger line truncation raises potential safety concerns relating, for example, to loss of mechanistic positive definite feed of cold water into the bottom plenum of the fuel racks, bypassing of water in the pool inlet/outlet region, inadequate cooling of hot fuel far from water inlet region and so forth. Demonstration of adequate cooling of spent nuclear fuel therefore requires a rigorous quantification of the velocity and temperature fields in the spent fuel pool. The present paper presents results from rigorous Computational Fluid Dynamics (CFD) studies of the Kori-4 spent fuel pool. A discussion of new insights obtained from this and other studies is presented.

1. INTRODUCTION

In Korea, nuclear power has played an important role in the national energy production system since the first commercial operation of KORI-1 nuclear power plant in 1978. Since then, the nation's nuclear power program has continuously expanded. At present, Korea has nine operating nuclear power plants (8 PWRs and 1 CANDU) with a total installed generating capacity of 7,616 MWe. The nuclear share of Korea's total installed electrical generation capacity is about 36 %. To support this level of power generation base the power plants require approximately 180 MTU of PWR fuels

and 100 MTU of CANDU fuels every year. Additionally, seven new nuclear power plants, with a capacity of 6,100 MWe, are currently under construction. The new units are planned to be connected to the electric grid by the year 2006.

There are several long-term issues to be resolved in order to continue the Korean nuclear energy program as planned. One of the major issues is the radioactive waste management which will eventually require interim spent fuel storage, and low- and intermediate-level radioactive waste disposal. The on-site spent fuel pool storage capacity at most of Korean nuclear power plants will be completely used up by about year 2000. To resolve this impending issue, the Korean Atomic Energy Commission, the governmental regulating authority, decided in 1988 that a central away-from-reactor interim storage facility for spent fuel will be constructed by December 1997. As a result of this decision, several studies on proposed scenarios for interim storage of spent fuel have been performed. Meanwhile, progress on construction of an interim storage facility has been handicapped due to site selection difficulties. This has resulted in Korea's nuclear power plant utility (KEPCO) to opt for reracking of existing spent fuel pool facility to increase the at-reactor storage capacity. High Density Storage Racks(HDSRs) have been installed in Kori-4 nuclear power plant recently and will be installed in Yonggwang(YGN)-1 & 2 nuclear power plants to maximize fuel storage capacity. In this paper, the resolution of potential safety concerns encountered in the present Kori-4 reracking project, are presented and the results of rigorous analyses to qualify pool thermal-hydraulics in the post sparger truncation scenario are discussed.

2. RERACKING PROJECTS FOR OPERATING PLANTS IN KOREA

Spent fuel storage racks ensure safe storage of spent fuel under normal and postulated accident conditions. The fuel storage racks are designed to withstand operating loads (dead loads of fuel assemblies) as well as safe shutdown earthquake loads, as required by Category I seismic requirements of Regulatory Guide 1.29. As of May 1996, a total of 3,515 fuel assemblies (1,437 tons of uranium) at 8 PWRs and 62,772 fuel bundles (1,186 tons of uranium) for the single CANDU unit have been discharged to the spent fuel pools. A dry storage facility was installed to increase the storage capacity for the CANDU spent fuel in 1992. CANDU spent fuel is stored in a dry storage facility after being cooled for 10 years in a wet storage pool. Reracking projects at Kori-3, Kori-4 and Ulchin(UCN)-1 & 2 have completed and reracking projects at YGN-1 & 2 are in progress.

Design parameters of KORI-4 and YGN-1 & 2 plants are essentially similar to those of KORI-3 unit. Both KORI-4 and YGN-1 have been in commercial operation since 1986 and YGN-2 has been in operation since 1987. As of December 1995, KORI-4, YGN-1 and YGN-2 have stored 524, 476, and 424 spent fuel assemblies, respectively. It is expected that existing KORI-4 and YGN-1 storage capacity

(746 fuel assemblies for each plant) will be fully used up in 1997 and the YGN-2 fuel pool will be full in 1999. Therefore, installation of HDSRs is scheduled for 1996 through 1997 for all three units. Following the utility's requirements, the new HDSRs to be installed in empty spaces of the current pool configuration are designated as region I racks. Existing racks will be designated as region II racks. On completion of the reracking project, a total of 1218 additional cells (i.e. 406 storage cells for each plant) in HDSR racks will be available for spent fuel storage. Design parameters for the spent fuel pools at the reracked nuclear power plants are summarized in Table 1.

3. MODIFICATION OF SPENT FUEL POOL COOLING SYSTEM

In the Kori-4 and YGN-1 & 2 reracking campaign, KEPCO has planned to remove a part of the spent fuel pool cooling piping and supports in order to prevent their interference with HDSRs installation and thus maximize fuel pool storage capacity. To prevent any potential reduction in the ability to cool the stored nuclear fuel in the modified pool cooling system configuration, an in-depth analysis of the pool, using state of the art CFD methodology, was performed.

A. Cutting of Underwater Cooling Pipe

Figure 1 shows the existing and post rerack campaign racks and cooling system configuration. The spent fuel pool cooling system consists of two identical discharge paths, which join and then split to the north and the south side of the pool. The cooling lines drop to the bottom of the pool and run along the North and South pool walls. The bottom of pool sparger pipe runs are provided with a large number of drilled holes for distributing the incoming cold water to the bottom of the fuel storage rack cells. The north side pipe branch will be truncated and the bottom of pool sparger pipe run removed to enable HDSR installation. Cutting of underwater pipe and related modifications will be performed by 3 underwater divers.

Removal of the north side pipe branch with an open discharge into the pool at the truncation location would have resulted in a decreased cooling water flow in the south side branch and reduced overall spent fuel cooling system hydraulic resistance. For ensuring North and South side flow balance and to eliminate potential safety concerns related to spent fuel pool pump runout, a 90° pipe bend with a flow resistance element will be added at the pipe truncation point to direct flow toward the bottom of the pool. The flow resistance component consists of a flow restriction designed to provide an equivalent head loss of the cut and removed section of cooling pipe. The original design of the cooling pipe proposed to be removed specified a total loss of 2.5 psi at the design flow rate of 3500 gpm. The modified north side line is designed with the same total resistance at the design flow rate.

B. Major Licensing Issues

While sparger line truncation has become a standard pool modification item in rerack campaigns in recent years, it was viewed by KINS (Korea Institute of Nuclear Safety) to be a significant safety concern on first trial in Korea. KINS (Korean regulatory body), therefore raised several questions relating to radiation safety during underwater cutting and the thermal-hydraulic conditions after sparger line truncation. In the thermal-hydraulic area, particular emphasis was placed on the following technical items by the KINS:

- Adequacy of the thermal-hydraulic model
- Thermal-hydraulic analysis conservatisms
- Bypassing of cold water from inlet to outlet
- Inadequate cooling of the hot fuel cell locations

A discussion of the CFD modelling approach and the results obtained is provided in the next section.

4. SPENT FUEL POOL THERMAL SPACE EVALUATION BY CFD METHODOLOGY

At an early stage in the thermal-hydraulic study of KEPCO's spent fuel pool, it was recognized that a rigorous computation of flow and temperature fields was required to qualify the sparger truncation modification to the fuel pool. Rigorous modeling of fluid flow problems requires a solution to the classical Navier-Stokes equations of fluid motion [1]. The equations (in modified form for turbulent flows with buoyancy effects included) are provided below:

$$\frac{\partial \rho_o u_i}{\partial t} + \frac{\partial \rho_o u_i u_j}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{\partial p}{\partial x_i} - \rho_o \beta (T - T_o) g_i + \frac{\partial \rho_o \left\langle u_i' u_j' \right\rangle}{\partial x_j}$$

where, u_i are the three time-averaged velocity components, $\rho\left\langle u_i' u_j' \right\rangle$ are time-averaged Reynolds stresses derived from the turbulence induced fluctuating velocity components u_i', ρ_o is the fluid density at temperature T_o, β is thermal expansion coefficient, μ is the fluid viscosity, g_i are the components of gravitational acceleration and x_j are the cartesian co-ordinate directions. The Reynolds stress tensor is expressed in terms of the mean flow quantities by defining a turbulent viscosity μ_t and a turbulent velocity scale $k^{1/2}$ as shown below [2]:

$$\rho\left\langle u_i' u_j' \right\rangle = 2/3 \rho k \delta_{ij} - \mu_t \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right]$$

The procedure to obtain the turbulent viscosity and velocity

length scales involves a solution of two additional transport equations for kinetic energy(k)and rate of energy dissipation(ε). This methodology is known as the k-ε model for turbulent flows as described by Launder and Spalding [3].

A closed form analytical solution of the Navier-Stokes equations is possible for only the simplest of geometries (e.g. pipe flow). For more complex situations, as in the spent fuel pool study, a numerical solution of the governing equations with appropriate boundary conditions is a feasable alternative using available CFD tools. The CFD analysis methodology permits modeling of the detailed geometry consisting of fuel racks, inter-rack gaps, bottom plenum, downcomer, water inlet/outlet and bulk pool regions. The pool geometry requires an adequate portrayal of large scale and small scale features, application of spatially distributed heat sources in the spent fuel racks and water inlet/outlet configuration. Relatively cooler bulk pool water normally flows down the narrow fuel racks to pool wall liner clearance known as the downcomer. Near the racks bottom, the flow turns from a vertical to horizontal direction into the bottom plenum supplying cooling water to the rack cells. Heated water issuing out of the top of the racks mixes with the bulk pool water. An adequate modeling of these features on the CFD modeling package involves meshing the large scale (bulk pool) and small scale (downcomer, bottom plenum etc.) regions with sufficient number of computational cells to capture the bulk and local features of the flow field.

Several pessimistic assumptions, listed below, are incorporated in the CFD model to guarantee a conservative portrayal of the temperature field in the spent fuel pool:

(i) Cooling from spent fuel pool surface and side walls are neglected.

(ii) The water inlet at the truncation point is directed horizontally to maximize cold water bypass of the hot fuel stored in the pool. In reality, the vertically downward directed jet of cold water would mix with the downcomer water thus lowering the temperature of water flowing towards the bottom inlet of the rack cells.

(iii) The hot freshly discharged fuel assemblies are stored in the much more tightly spaced HDSR cells in the most adverse location in the middle region of the high density rack layout. This conservatively maximizes resistance to water flow in the bottom plenum.

(iv) Radial peaking effects are included by assuming that half the full core discharge fuel rack cells are loaded with hotter than an average fuel assembly.

In Figure 2, a finite element mesh of the computational domain representing a planar East-West section of the high density fuel racks is shown. Applied heat generation in the fueled region of the computational domain depicted by the "H" symbol is shown in the same Figure. An inset near the top left of the Figure depicts a locally fine mesh chosen to resolve the bottom plenum and downcomer region near the bottom left edge of the fuel pool. Fuel pool temperature distribution and velocity vector results obtained from this CFD model are depicted in Figures 3 and 4.

Results of the CFD analysis confirm the well mixed bulk pool hypothesis (the temperature variation is within a few degrees). The hot fuel located in the high density fuel storage cells is adequately cooled by the sub-cooled water in all regions. As expected, a local temperature peak has developed near the exit of one of the rack cells in the middle. Results of the CFD analysis show that for an unrealistic horizontally directed water jet scenario from the West pool wall, water bypass across the length of the pool is not a credible possibility. The cold jet of more dense water (see gray colored temperature band between 114.0 and 117.0 degrees F in Figure 3) is observed to descend on a region near the top of the racks and locally quench a portion of the hot fueled racks. A rigorous modeling of KEPCO's spent fuel pool enabled the utility to answer all regulatory concerns on the issue of sparger truncation and obtain a license for installing high density racks. The Kori-4 experience has been confirmed at other nuclear plants.

At another nuclear plant site (Millstone Unit-1), location of an integral circulating pump/filter unit discharge lines near top of racks raised safety concerns relating to local flow blockage, flow stagnation in the racks and inadequate mixing in the bulk pool. This portable in-situ pump/filter unit was used to take suction from the bulk pool, extract particulates in a filter bed and route the water back to the pool. Prior to these concerns, a three dimensional CFD analysis of the pool without the pump/filter unit was undertaken by Holtec. A plot of the three dimensional fuel pool temperature distribution is shown in Figure 5. The cooling produced by the jet of incoming water (blue contour band) from the truncated sparger is readily apparent in this Figure.

A close scrutiny of the bulk pool flow distribution near top of racks suggested a conservative approach to model the orientation of the pump/filter unit discharge to maximize flow stagnation conditions. Under normal conditions, the pump/filter water discharge was routed through a flexible hose sitting on top of the racks in an arbitrary orientation. The existing CFD model was modified to include the pump/filter unit with it's suction and discharge lines. A worst case orientation of the discharge was chosen to directly oppose the bulk flow with an intent to induce flow stagnation conditions on top of the racks. Results of the analysis are shown in Figures 6 to 8. A plan view of the top of racks flow field in the absence and presence of the pump/filter

unit is shown in Figure 6 and 7 respectively. In Figure 8, a three dimensional view of the flow field showing the storage racks, pump/filter unit and two pipe discharges is depicted. Results of the analysis conclusively demonstrated that flow stagnation resulting from use of the pump/filter unit was not a credible possibility.

5. RESULTS AND DISCUSSION

An impending loss of at-reactor spent fuel storage capacity was an issue requiring an effective time critical solution to continue the Korean nuclear energy production program. Reracking existing pools was judged to be the first option to increase the at-reactor spent fuel storage capacity after alternative plans to transfer fuel to a centralized away-from-reactor interim storage facility were found to be behind schedule. The spent fuel pool reracking projects at UCN-1 & 2 and KORI-3 are examples of exercising such an option in the past. Reracking of KORI-4, YGN-1, and YGN-2 was a new step designed to maximize utilization of existing fuel pool space and therefore fuel storage capacity with the installation of HDSRs. Sparger line truncation was considered to be an effective strategy for implementing these goals.

CFD tools have paved the way for performing rigorous local thermal-hydraulic studies required for fuel pool safety evaluation and licensing in the wake of new design issues and concerns requiring timely resolution. Sparger line truncation is a significant design issue requiring a rigorous study to muster licensing support and meet utility goals to maximize fuel storage space. CFD studies have played a pioneering role in resolution of safety concerns related to flow bypassing, flow stagnation resulting from operation of pump/filter units in fuel pools and a study of flow induced erosion of Boraflex racks. These techniques are expected to play an increasingly critical role in the future for licensing and qualification of spent fuel pools.

REFERENCES

1. Batchelor, G.K., An Introduction to Fluid Dynamics, Cambridge University Press, 1967.

2. Hinze, J.O., Turbulence, McGraw Hill Publishing Co., New York, NY, 1975
3. Launder, B.E., and Spalding, D.B., Lectures in Mathematical Models of Turbulence, Academic Press, London, 1972.

Table 1. Spent Fuel Pool Design Parameters at Nuclear Power Plants in Korea

PLANT	UCN-2	KORI-3	UCN-1	KORI-4 YGN-1 YGN-2	Remarks
RATED POWER (MWe)	920 MWe	895 MWe	920 MWe	895 (KORI-4) 900 (YGN-1,2)	
CORE SIZE(FA)	157	157	157	157	
NORMAL DISCHARGE	40 FAs/yr	44 FAs/yr	40 FAs/yr	44 FAs/yr (Kori-4) 40 FAs/yr (YGN-1&2)	
FUEL TYPE	F STD KOFA WH V-5H	WH STD WH OFA KOFA	F STD KOFA WH V-5H	WH STD(KORI-4 only) WH OFA KOFA WH V-5H	
RERACKING CONCEPT	1st Rerack: Complete Replacement 2nd Rerack: Partial Replacement	Expansion	Complete Replacement	Expansion (on-going)	In UCN-2, boraflex racks were replaced partially with boral racks during 2nd reracking. Remaining boraflex racks will be used as Region II racks.
INITIAL STORAGE CAPACITY(FAs)	472 (9/3 core)	746 (14/3 core)	472 (9/3 core)	746 (14/3 core)	
EXPANDED CAPACITY(FAs) - Region I - Region II	893/875 (1st/2nd Rerack) 893/234 (1st/2nd Rerack) 0/641 (1st/2nd Rerack)	1201(1189 possible) 746 455	1114 264 850	1152 406 746	
Fas IN STORAGE	252	736	321	524(KORI-4) 476(YGN-1) 424(YGN-2)	As of Dec.1995
EXPECTED POST RERACKING SATURATION YEAR	2006	2002	2010	2006(KORI-4) 2007(YGN-1) 2009(YGN-2)	
NEUTRON ABSORBER - Region I - Region II	- Boral - Boraflex	- Austenitic st. st. - Borated st. st.	- Boral - Boral	- Boral - Austenitic st. st.	

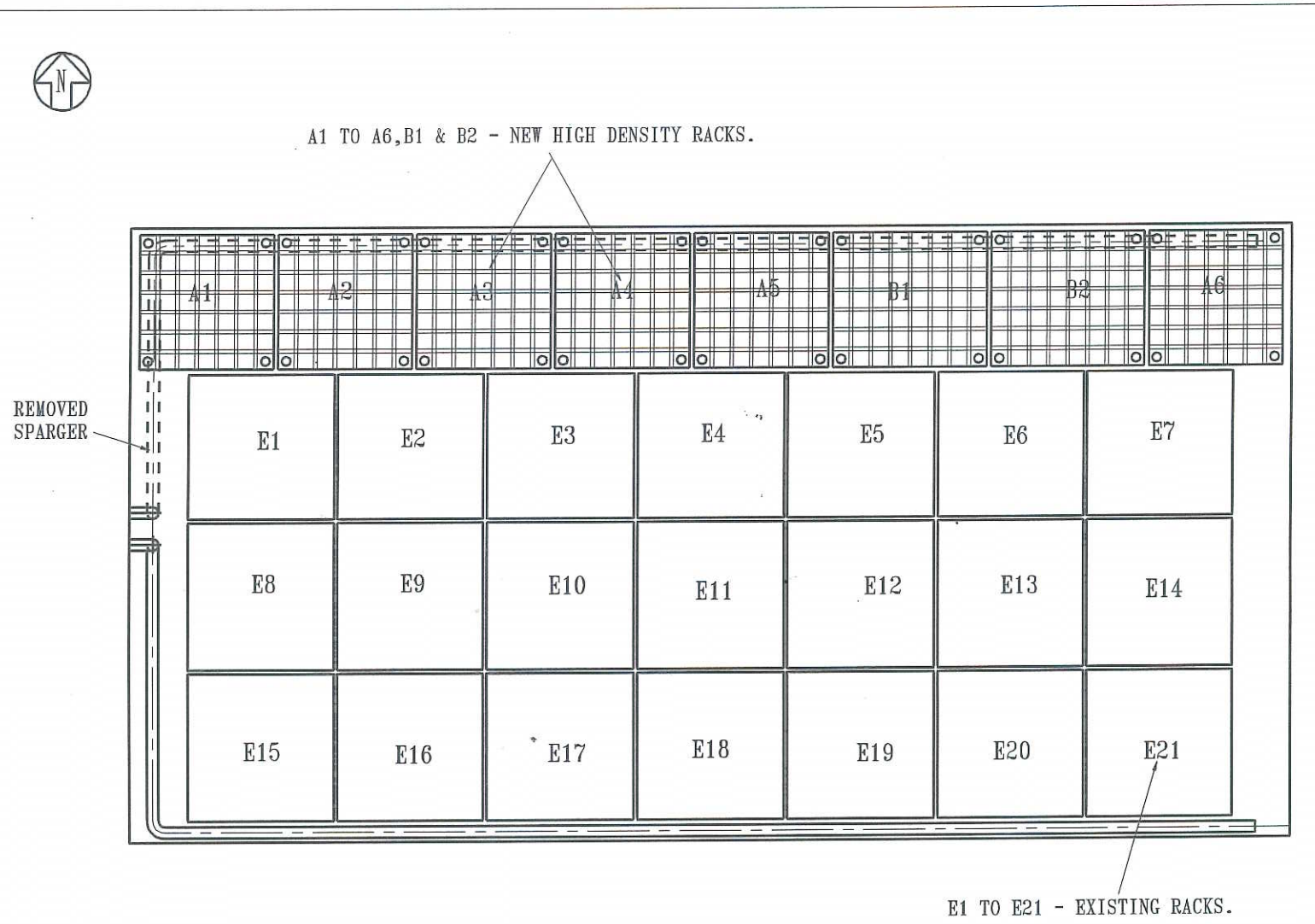

FIGURE 1; SPENT FUEL POOL RACKS LAYOUT

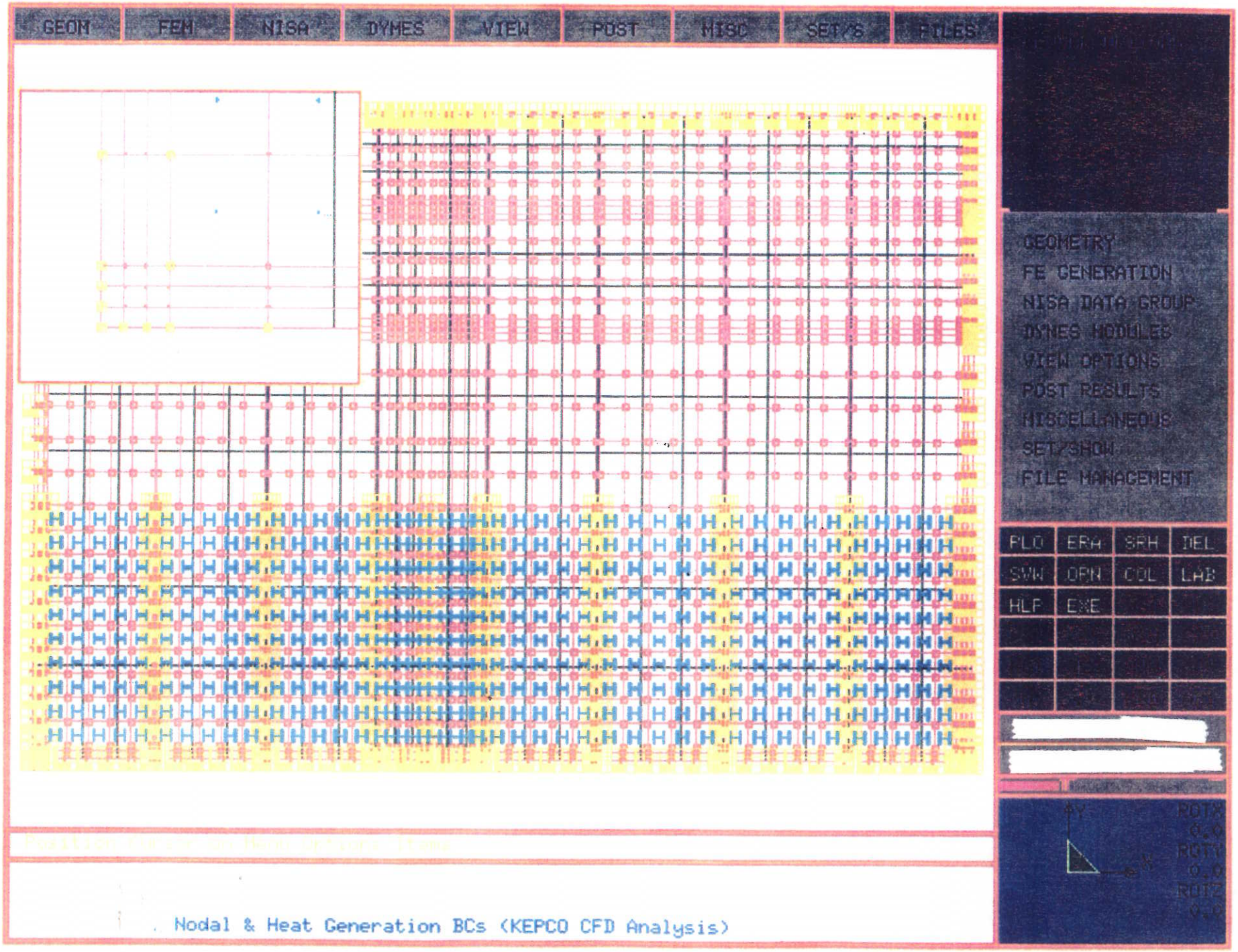

FIGURE 2: CFD MODELLING - FUEL POOL FINITE ELEMENT MESH

FIGURE 3: CFD ANALYSIS RESULTS - FUEL POOL TEMPERATURE CONTOURS

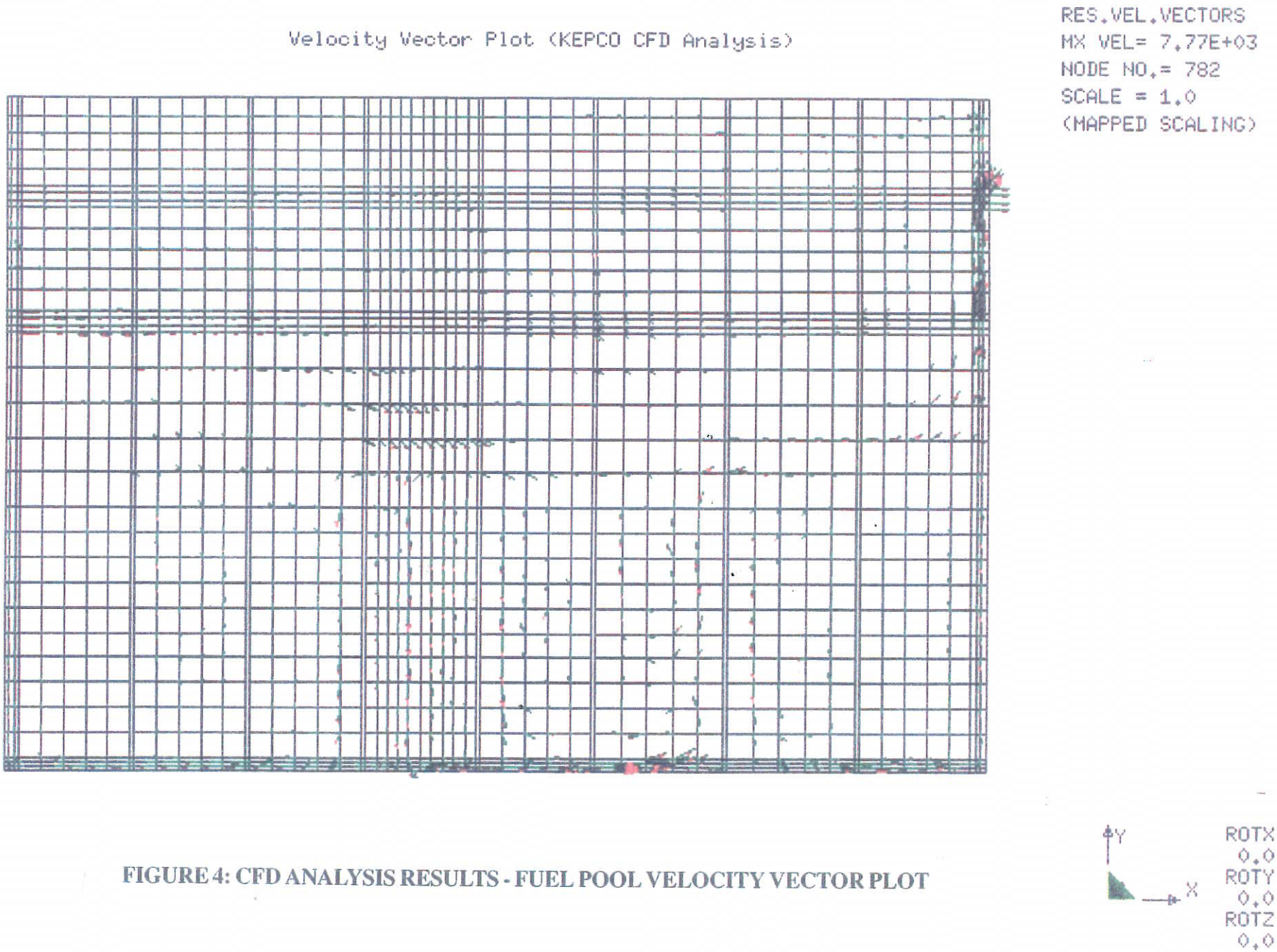

FIGURE 4: CFD ANALYSIS RESULTS - FUEL POOL VELOCITY VECTOR PLOT

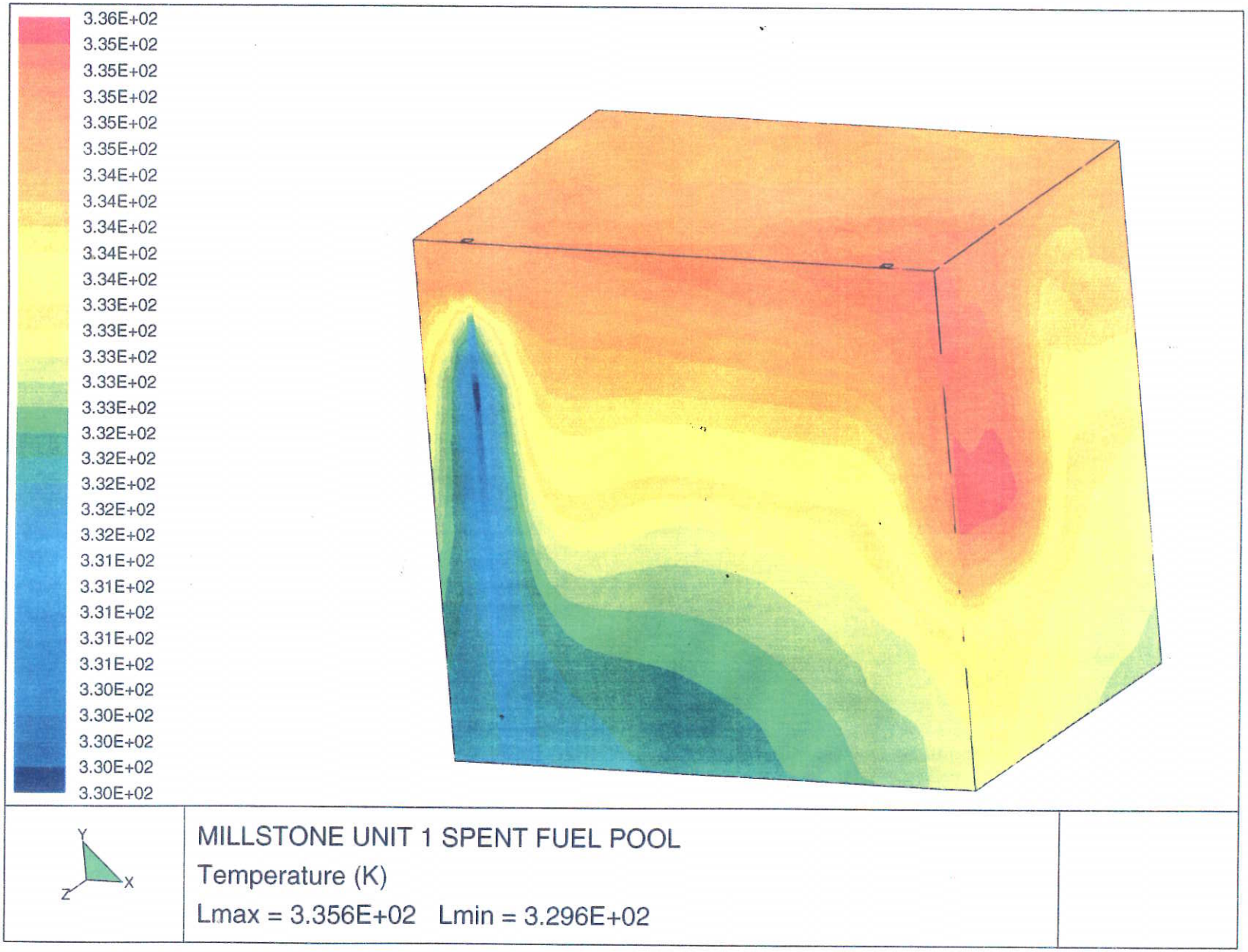

FIGURE 5: MILLSTONE POOL 3-DIMENSIONAL TEMPERATURE CONTOUR PLOT

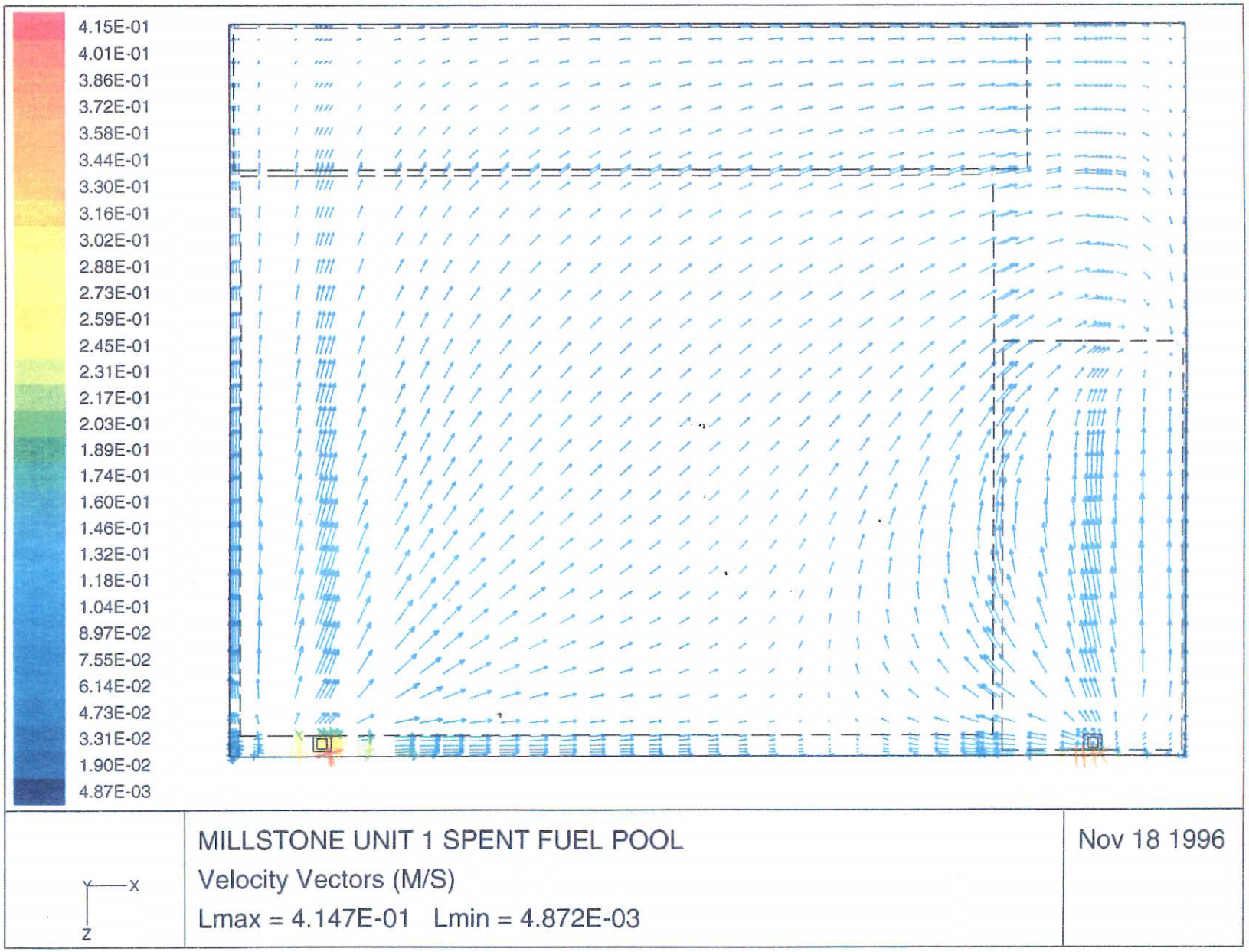

FIGURE 6: FLOW FIELD ON TOP OF MILLSTONE POOL RACKS BEFORE INSTALLATION OF PUMP/FILTER UNIT

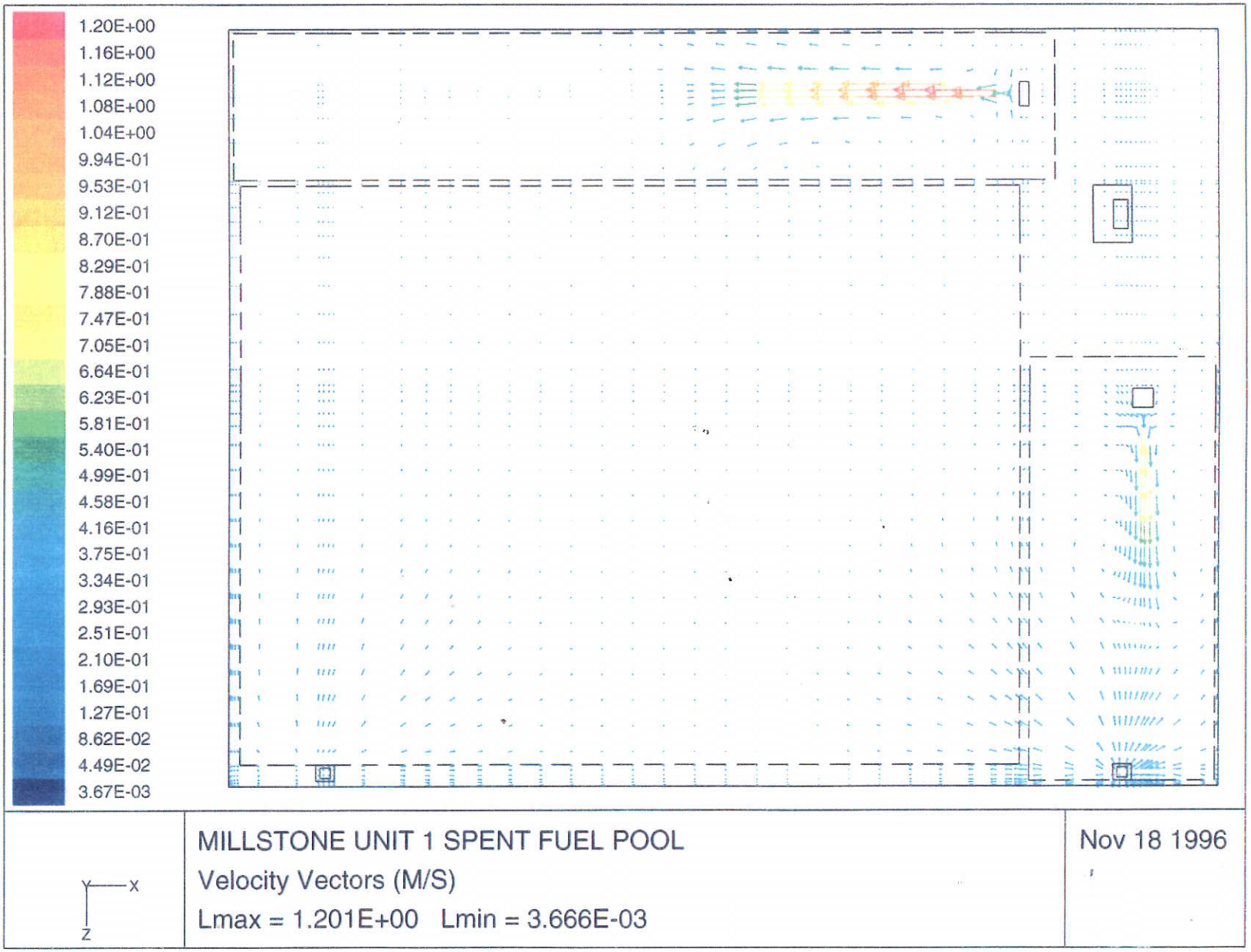

FIGURE 7: FLOW FIELD ON TOP OF MILLSTONE POOL RACKS AFTER INSTALLATION OF PUMP/FILTER UNIT

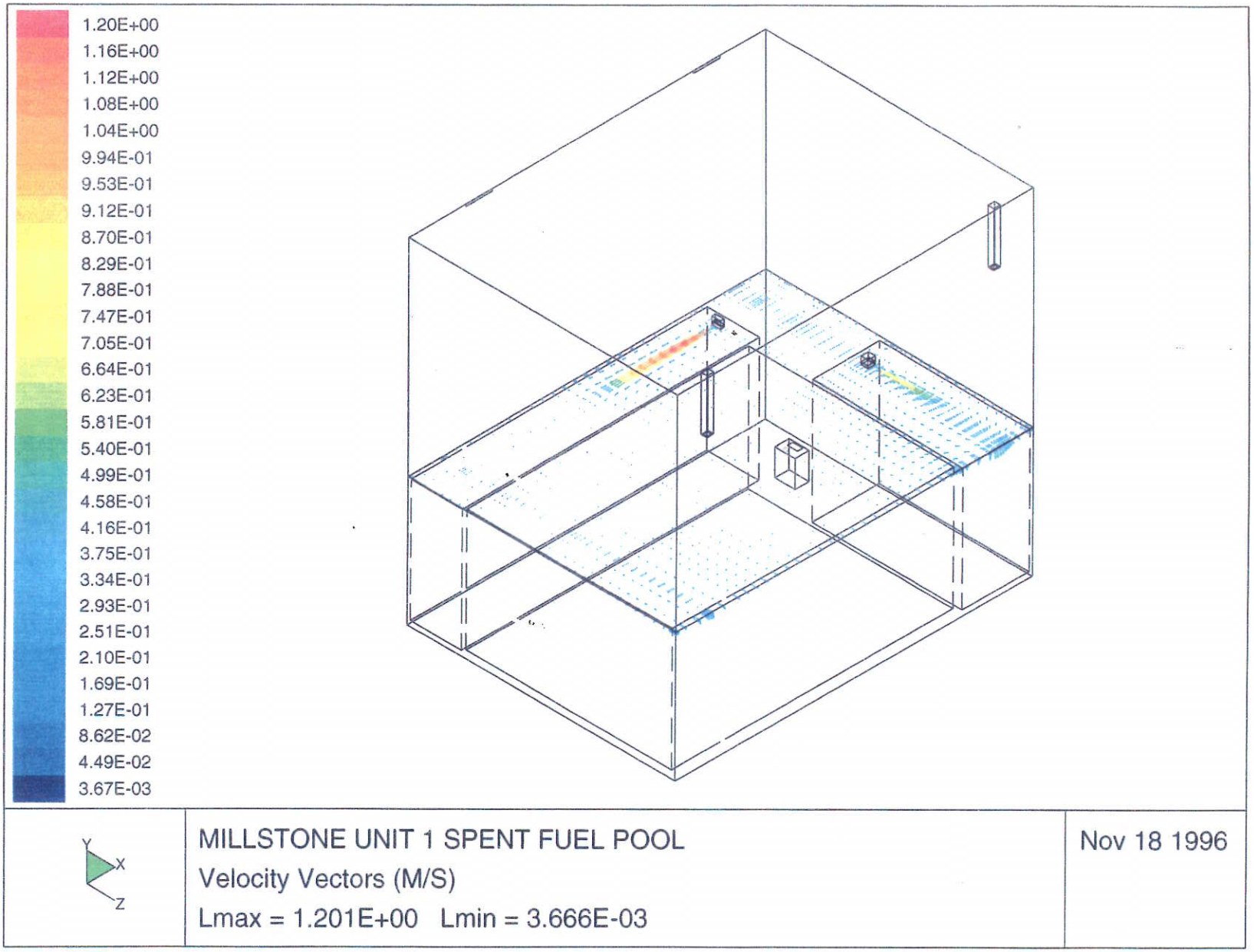

FIGURE 8: 3-DIMENSIONAL VIEW OF MODIFIED MILLSTONE POOL FLOW FIELD