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CALCULATION PACKAGE

CALCULATION NO:	NUH32PT.0414	**PROJECT NAME:**	NUHOMS® 32PT Design
PROJECT NO:	NUH 32PT	**CLIENT:**	Transnuclear, Inc.

CALCULATION TITLE:

Validation of FLUENT™/ ICEPAK™ For Convective Flow In Enclosures

SUMMARY DESCRIPTION:

This calculation provides the validation of the FLUENT™/ ICEPAK™ suite of software codes for computing the heat transfer within an enclosure. FLUENT™/ ICEPAK™ are used in combination with each other to setup, analyze, and post-process thermal-hydraulic based problems using computational fluid dynamics (CFD) modeling. This validation is performed for modeling convective flow in enclosures only. The validation of other portions of the codes is not part of this validation. This validation is only applicable to the heat transfer within the cavities of the OS197 transfer cask neutron shield.

NON-PROPRIETARY, FOR INFORMATION ONLY

REVISION	TOTAL PAGES AND DISKS (IF ANY)	NAMES AND INITIALS OF PREPARERS & DATES	NAMES AND INITIALS OF VERIFIERS & DATES	APPROVER NAME AND SIGNATURE	APPROVAL DATE
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* Proprietary Information - Intentionally Left Out.

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REVISION SUMMARY

REV.	DATE	DESCRIPTION	AFFECTED PAGES	AFFECTED DISKS
0	4/03/03	Initial Release	ALL	N/A

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1. INTRODUCTION

1.1 Objective

The FLUENT™ [6.2] and ICEPAK™ [6.3] codes are used in combination with each other to setup, analyze, and post-process thermal-hydraulic based problems using computational fluid dynamics (CFD) modeling. The objective of this calculation is to calculate the heat transfer within a generic enclosure for a variety of conditions using the FLUENT™/ ICEPAK™ suite of software codes. The input and output from these analyses are compared to textbook solutions for the same type of problem to validate the FLUENT™/ ICEPAK™ codes for computing the heat transfer within an enclosure.

1.2 Purpose

It is proposed to use the FLUENT™/ ICEPAK™ codes for evaluating the effective thermal conductivity within the various enclosures that make up the neutron shield of the OS197 transfer cask. The FLUENT™/ ICEPAK™ codes are to be used as project specific category 2 (limited application) software programs for this purpose. The purpose of this calculation is to provide the project specific validation of these codes for that application.

1.3 Scope

The scope of this calculation is limited to natural convection heat transfer within an enclosure using the FLUENT™ code, Version 5.6 [6.2] with the ICEPAK™ module, Version 4.08 [6.3]. The source code for these software packages are not modified for this application. They are the same as were provided via References [6.2] and [6.3].

2. VALIDATION CASES

A validation test geometry consisting of a horizontal enclosure with an aspect ratio of 1.0 is used. This geometry is selected since analytical and experimental data exists for this geometry for wide range of Rayleigh and Prandtl number fluids. By evaluating the convective heat transfer within the enclosure for a range of Rayleigh and Prandtl numbers, the general applicability of the FLUENT™/ ICEPAK™ codes for evaluating heat transfer in an enclosure can be validated. The validation testing was conducted for a Dell workstation computer with dual Xeon processors and the Windows XP Professional operating system.

Figure 1 illustrates the test geometry used for this analysis. The test geometry consists of a 6-inch high (i..e., y-axis) and 6-inch long (i..e., x-axis) enclosure. Since the enclosure is assumed to be extensive in depth, the depth (i..e., z-axis) is immaterial to the problem. However, for the purposes of this modeling, a 1.2-inch deep enclosure is utilized. Symmetry boundary conditions are imposed at the z = 0.0 and z =1.2" boundaries. The wall at the minimum x-axis position (i.e., the 'Hot Wall') has a fixed heat flux boundary condition, while the wall at the maximum x-axis position (i.e., the 'Cold Wall') is held at a fixed temperature. The top and bottom boundaries (i.e., y = 6" and y = 0", respectively) are assumed to be adiabatic, non-conducting boundaries.

The solution to the heat transfer within this type of cavity has been addressed by numerous investigators. Figure 4 presents a table from [6.1] which tabulates the numerically computed Nusselt numbers from a variety of sources for vertical enclosures of the type modeled for this validation. As seen, the table presents the textbook or reference Nusselt numbers for a range of Rayleigh number (Ra) and Prandtl number (Pr). Figure 5, also from [6.1], illustrates the variation of Nusselt number vs. cavity aspect ratio and Rayleigh number. This validation evaluates four (4) combinations of Rayleigh number, Prandtl number and aspect ratio for comparison with the Figure 4 reference solutions.

For the purposes of this analysis, the fluid filling the enclosure can be an arbitrary fluid since the results will be correlated using Rayleigh number (Ra). The Rayleigh number for an enclosure is computed as follows:

$$Ra_L = \frac{\rho^2 g_c \beta L^3 \Delta T}{\mu^2} \times Pr$$

where:

g_c = gravitational acceleration
β = coefficient of thermal expansion
Pr = Prandtl number
ΔT = temperature difference across enclosure
ρ = density of fluid
μ = dynamic viscosity of fluid
L = characteristic length (i.e., distance between the vertical boundary walls)

For the purposes of this validation, four (4) simulated fluids are used to generate a range of Rayleigh numbers. The properties chosen for three (3) of these fluids simulate a Pr ≈ 0.7 fluid that are similar to those for air, but whose properties have been adjusted to yield a Rayleigh number within a desired range for the specific validation case. The specific thermo-physical properties used are as follows:

<u>Fluid #1</u>

g_c = 32.174 ft/sec^2
β = 0.0012925/°R
L = 0.5 ft
ΔT = temperature difference obtained from model results
ρ = 0.075 lbm/ft^3
μ = 1.59e-4 lbm/sec-ft
κ = 5.738e-5 Btu/sec-ft-F°
c_p = 0.24 BTU/lbm-F°
Pr = $c_p\mu/\kappa$ = 0.67

<u>Fluid #2</u>

g_c = 32.174 ft/sec^2
β = 0.0012925/°R
L = 0.5 ft
ΔT = temperature difference obtained from model results
ρ = 0.075 lbm/ft^3
μ = 1.59e-5 lbm/sec-ft
κ = 5.738e-6 Btu/sec-ft-F°
c_p = 0.24 BTU/lbm-F°
Pr = $c_p\mu/\kappa$ = 0.67

Fluid #3

g_c = 32.174 ft/sec^2
L = 0.5 ft
ρ = 0.075 lbm/ft^3
κ = 5.738e-7 Btu/sec-ft-F°
Pr = $c_p\mu/\kappa$ = 0.67
β = 0.00006/°R
ΔT = temperature difference obtained from model results
μ = 1.59e-6 lbm/sec-ft
c_p = 0.24 BTU/lbm-F°

The properties chosen for the fourth fluid simulates a Pr ≈ 2 fluid that is similar to water. However, for the purposes of this calculation, specific properties have been adjusted to yield a Rayleigh number within a desired range. The specific thermo-physical properties used are as follows:

Fluid #4

g_c = 32.174 ft/sec^2
L = 0.5 ft
ρ = 62.0 lbm/ft^3
κ = 1.0079e-4 Btu/sec-ft-F°
Pr = $c_p\mu/\kappa$ = 1.98
β = 2.0e-9/°R
ΔT = temperature difference obtained from model results
μ = 2.0e-4 lbm/sec-ft
c_p = 1.0 BTU/lbm-F°

The Nusselt number (Nu) for an enclosure is defined as follows:

$$Nu = \frac{h_c \times L}{\kappa}$$

where:
- h_c = heat transfer coefficient between the 'Hot' and 'Cold' walls
- L = length of enclosure
- κ = thermal conductivity of fluid

The heat transfer coefficient, h_c, in turn is calculated as:

$$h_c = \frac{q_{Model}}{A \times \Delta T}$$

where:
- q_{Model} = heat flow between the 'Hot' and 'Cold' walls
- A = area of the 'Hot' or 'Cold' walls of enclosure
- ΔT = temperature difference between the 'Hot' and 'Cold' walls

3. FLUENT™/ICEPAK™ MODEL

The standard modeling functions within the FLUENT™/ ICEPAK™ codes are used to generate a thermal-hydraulic model of the Figure 1 geometry. The computational mesh is generated using an unstructured hexahedra mesh. Figure 2 illustrates the mesh arrangement for the FLUENT™/ ICEPAK™ model at the typical X-Y plane of the enclosure geometry. The mesh is generated using maximum mesh dimension of 0.05 inches in the X and Y directions and a maximum mesh dimension of 0.25 inches in the Z direction. Figure 3 presents the view of the mesh at the typical Y-Z plane.

The analysis is conducted for steady-state conditions for laminar flows.

The gravity vector for the model points in the negative Y axis direction and has a value of 32.174 ft/sec^2.

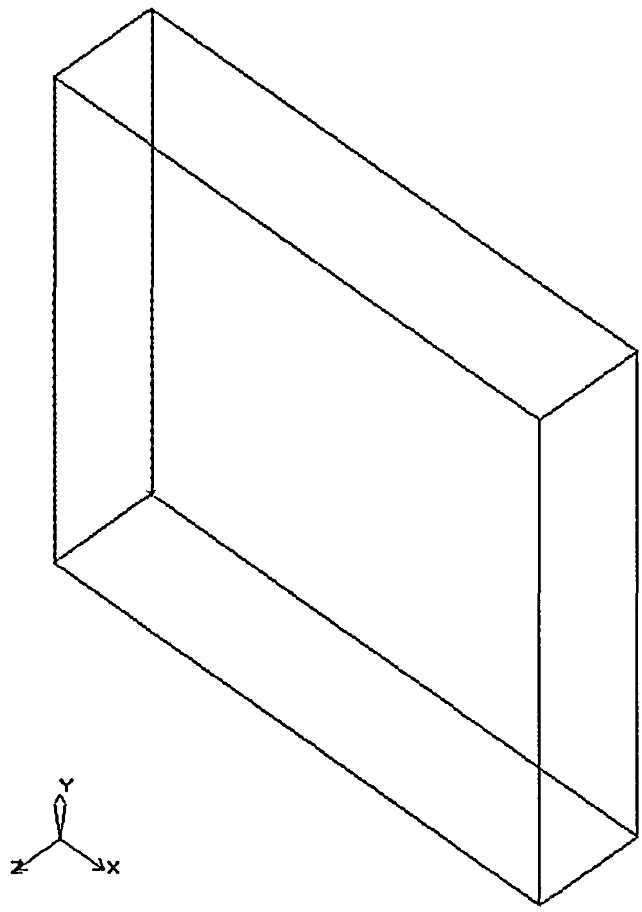

Figure 1 - Layout Of Enclosure Geometry For Validation Cases

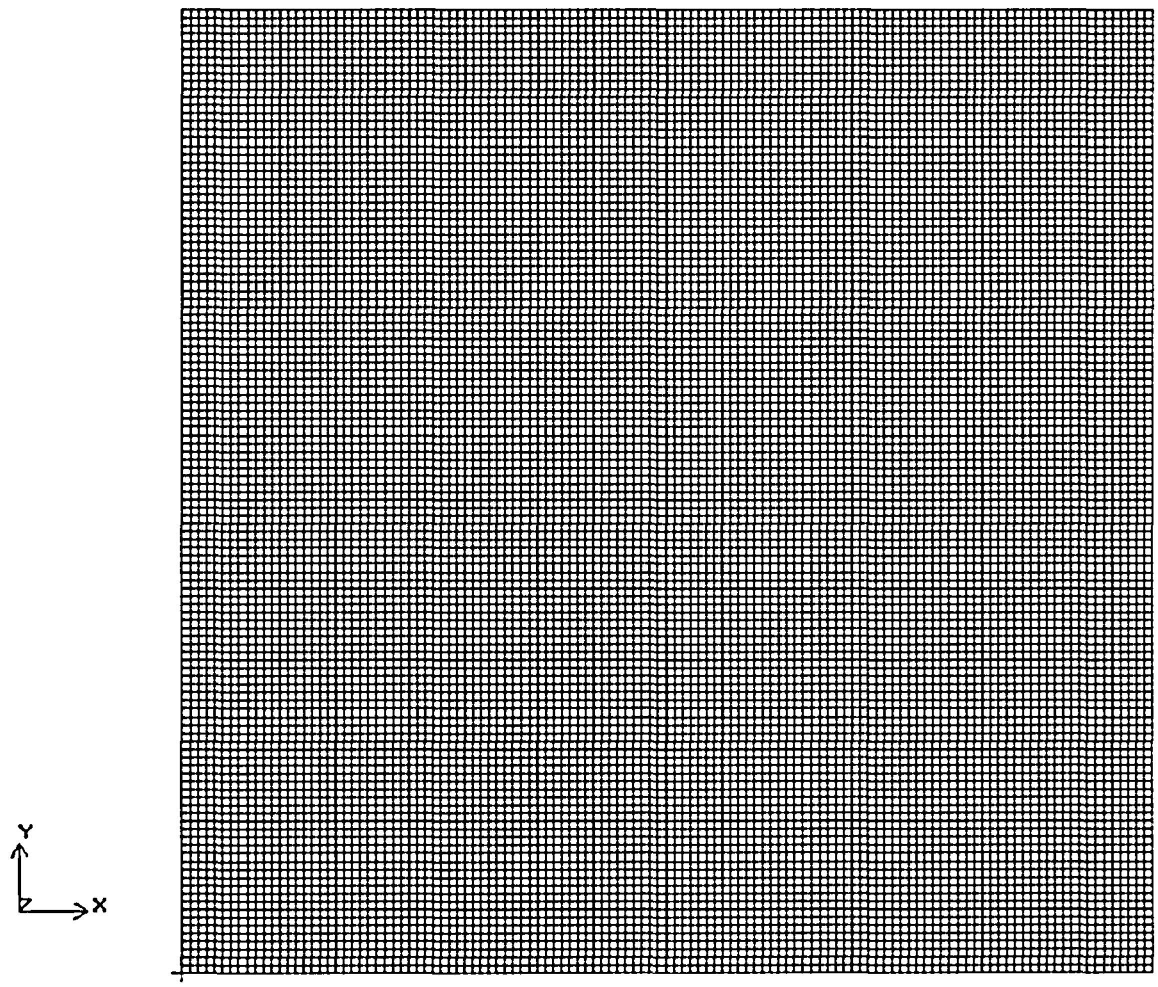

Figure 2 - Computational Mesh, View At Typical X-Y Plane

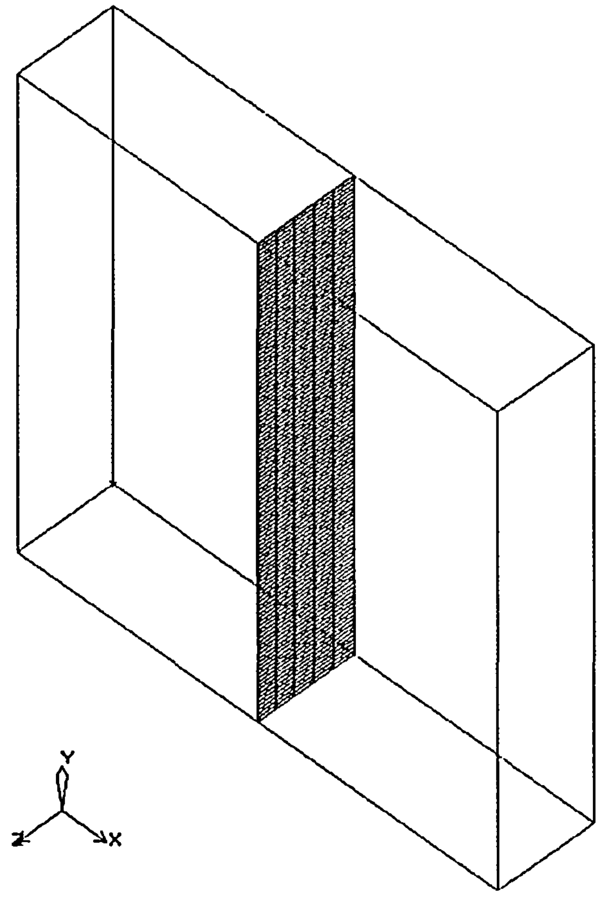

Figure 3 - Computational Mesh, View At Typical Y-Z Plane

TABLE 4.11 Tabulation of Numerically Computed Nusselt Number for Vertical ($\theta = 90°$) Rectangular Parallelepiped Cavities Having $W/L \gtrsim 5$ and $0.5 < H/L < 5$.

	H/L				
	0.5	1		2	5
Prandtl number	∞	0.7	∞	0.7	0.7
Reference	35	176, 230	35	230	230
Perfectly conducting walls					
$Ra = 10^3$	1.00	1.05	1.05	1.11	1.05
3×10^3	1.01	1.25	—	1.42	1.28
10^4	1.07	1.75	1.77	1.97	1.81
3×10^4	1.48	2.41	2.50	2.61	2.45
10^5	2.51	3.40	3.66	3.53	3.30
3×10^5	3.64	4.47	—	—	—
Adiabatic walls					
$Ra = 10^3$	1.00	1.12	1.12	1.19	1.09
3×10^3	1.05	1.50	—	1.64	1.39
10^4	1.30	2.24	2.24	2.34	2.00
3×10^4	2.18	3.14	3.16	3.12	2.72
10^5	3.82	4.51	4.52	4.26	3.68
10^6	—	8.83	—	—	—
10^7	—	16.52	—	—	—
10^8	—	30.22	—	—	—

See Fig. 4.25 for meaning of symbols.

Figure 4 - Re-creation of Table 4.11 from Ref. [6.1]

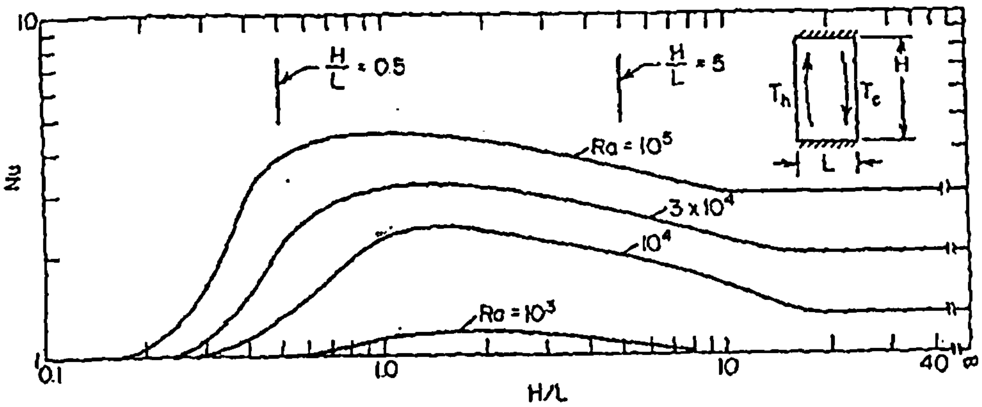

Figure 5 - Typical Nusselt Number For Vertical Cavity, Pr=0.7 from Ref. [6.1]

4. CALCULATIONS

Using the thermal model described in Section 3, the thermal-hydraulic environment within the enclosure was computed for the four test fluids. Since the Rayleigh number is a function of ΔT, the input heat to the model was varied between the four validation cases in order to yield a range of Rayleigh numbers for comparison with the reference solutions [6.1]. The heat flow and temperature difference between the 'Hot Wall' and the 'Cold Wall' are extracted from the model output results for each validation case. The Rayleigh number, convective heat transfer rate, and the effective Nusselt numbers are then computed using the model results, together with the fluid properties and the equations presented in Section 3.

Table 4-1 presents the model results and the computed Nusselt number, together with the reference Nusselt numbers from [6.1], for the selected validation cases. As seen from the table, the results compare favorably with the reference Nusselt numbers. The difference between the Nusselt numbers computed under this calculation and those from [6.1] for the four evaluated enclosure fluids are -2.6%, -1.7%, +2.0%, and -0.5%, respectively.

Figure 6 to Figure 13 present the temperature and velocity distribution for the four analyzed cases. The figures confirm the nearly isothermal end walls achieved for each analyzed condition. It should be noted there is a slight variation in temperature (<0.°1F) across the 'Hot Wall' due to the modeling technique employed. For the purposes of the calculations in Table 4-1, the average 'Hot Wall' temperature obtained from the model results is used.

The velocity distribution in Figure 7 is typical of a low Rayleigh number buoyancy driven flow in that the cellular flow is relatively extensive across the enclosure cross-section. As Rayleigh number increases, the cellular flow intensifies and becomes more concentrated in thin boundary layers adjoining the side walls (see Figure 9). While the flow profile illustrated in Figure 11 follows this trend, but the concentration of the flow into thin layers is less than what would normally be expected due to the low coefficient of the thermal expansion used for fluid #3. Figure 13 again illustrates the general cellular flow profile typical of a low Rayleigh number condition.

Table 4-1- Computed Nusselt Number For Aspect Ratio = 1.0 Enclosure

Enclosure Fluid #	Heat Flow, Btu/hr	Wall Temperature, °F		Computed Rayleigh No.	Computed h_c, Btu/hr-ft^2-°F	Computed Nusselt No.	Reference Nusselt No. From [6.1][2]
		Cold Wall	Hot Wall[1]				
1	1.00188	100	119.378	1.490×10^4	1.034	2.50	2.57
2	1.56528	100	156.221	4.323×10^6	0.557	13.48	13.72
3	1.4814	100	339.91	8.566×10^7	0.124	29.89	29.30
4	2.43288	100	120.873	3.202×10^4	2.331	3.21	3.23

Table Notes: (1) Wall temperature is the average across the face

(2) Via logarithmic interpolation from Table 4.11, Reference [6.1] – see Figure 4.

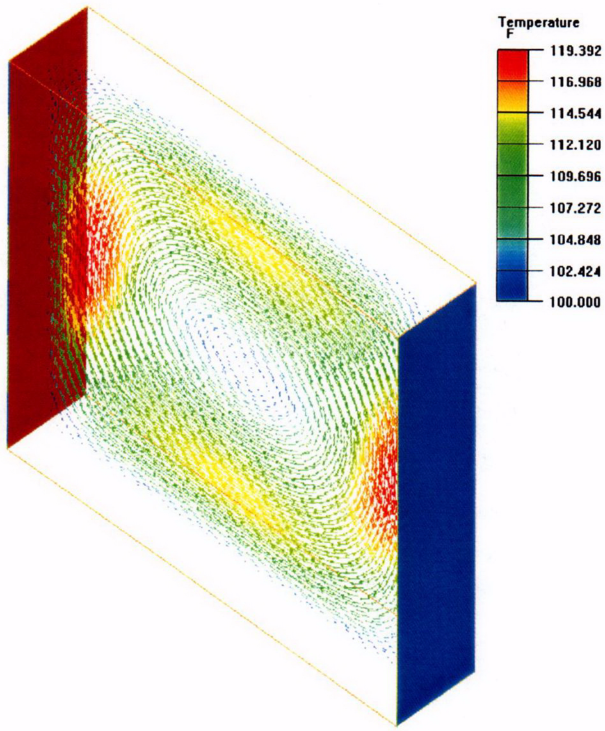

Figure 6 - Temperature Distribution For Enclosure With Fluid #1 (Ra ≈ $1.5x10^4$)

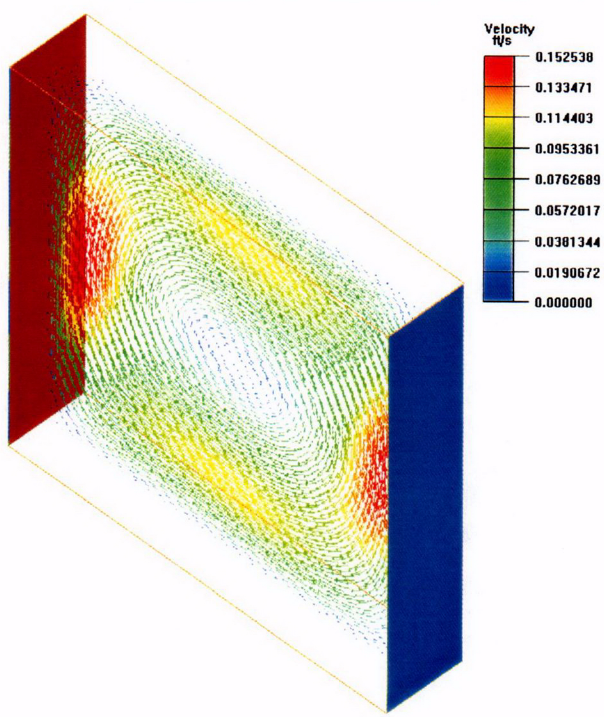

Figure 7 - Velocity Distribution For Enclosure With Fluid #1 (Ra ≈ $1.5x10^4$)

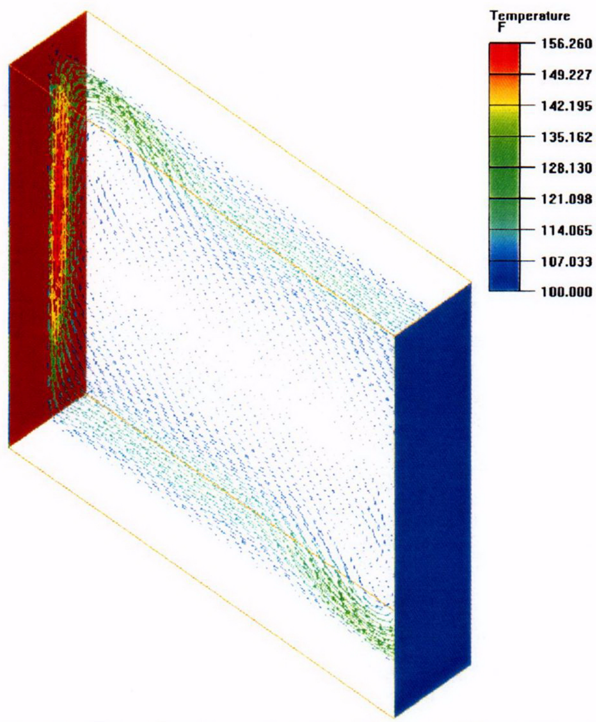

Figure 8 - Temperature Distribution For Enclosure With Fluid #2 (Ra ≈ 4.3x10^6)

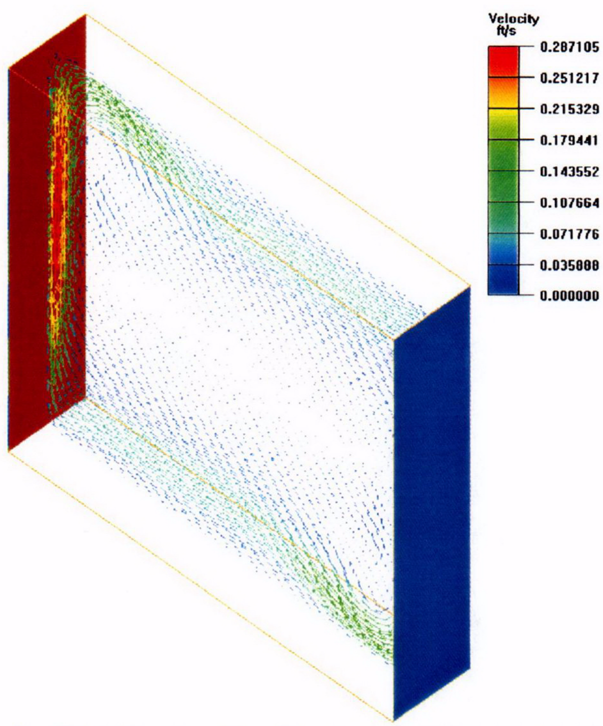

Figure 9 - Velocity Distribution For Enclosure With Fluid #2 (Ra ≈ 4.3x10^6)

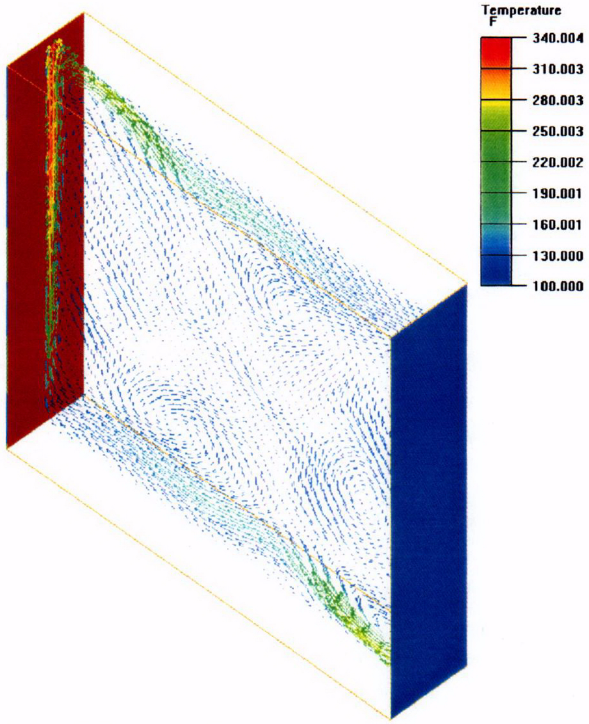

Figure 10 - Temperature Distribution For Enclosure With Fluid #3 (Ra ≈ 8.6×10^7)

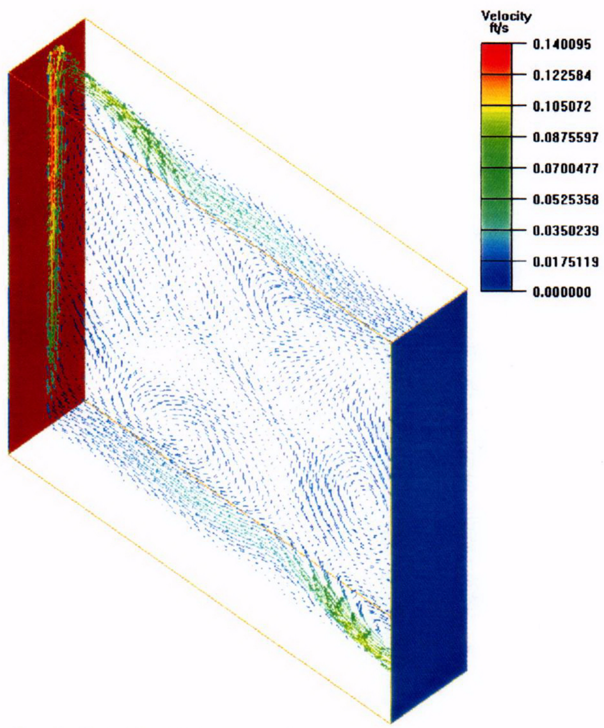

Figure 11 - Velocity Distribution For Enclosure With Fluid #3 (Ra ≈ 8.6×10^7)

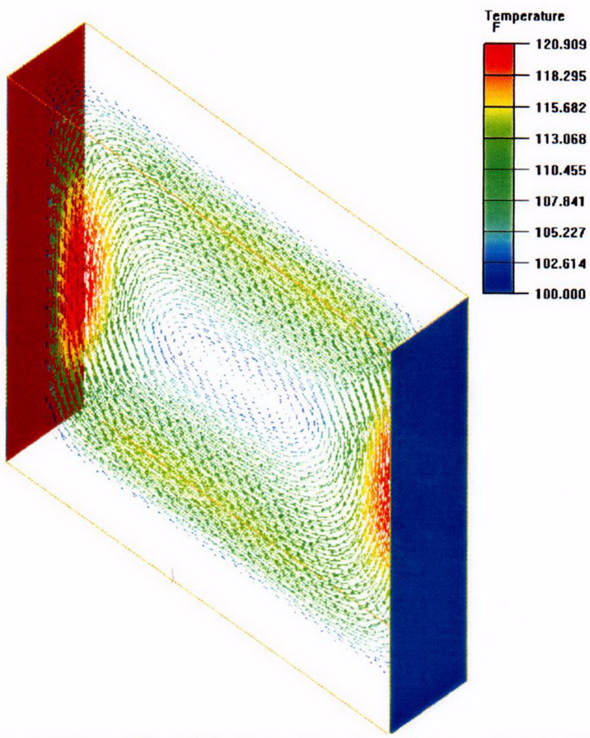

Figure 12 - Temperature Distribution For Enclosure With Fluid #4 (Ra ≈ $3.2x10^4$)

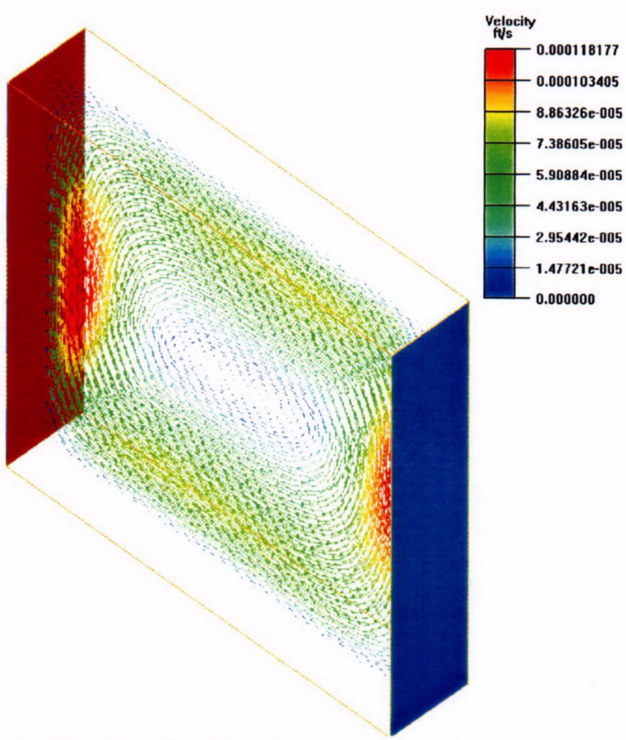

Figure 13 - Velocity Distribution For Enclosure With Fluid #4 (Ra ≈ $3.2x10^4$)

5. SUMMARY AND CONCLUSION

An evaluation of the heat transfer within a generic enclosure for four (4) flow conditions has been accomplished for the purposes of validating the FLUENT™ [6.2] and ICEPAK™ [6.3] codes. These validation analyses are conducted for the range of Rayleigh numbers expected within the various enclosures that make up the neutron shield of the OS197 transfer cask. The results of these analyses demonstrate that the FLUENT™/ ICEPAK™ codes will provide predicted Nusselt numbers that are within 2.6% of the reference Nusselt numbers for the same conditions, as provide by [6.1].

Based on these results, the FLUENT™/ ICEPAK™ codes are validated for use as project specific category 2 (limited application) software programs for the purpose of evaluating the heat transfer within the neutron shield of the OS197 transfer cask.

6. REFERENCES

6.1 *Rohsenow, Hartnett, and Cho, Handbook of Heat Transfer Fundamentals, 3rd edition, McGraw-Hill Publishers, 1998.*

6.2 *FLUENT™, Version 5.6, Fluent, Inc., Lebanon, NH, 2003.*

6.3 *ICEPAK™, Version 4.08, Fluent, Inc., Lebanon, NH, 2003.*

7. FLUENT™ / ICEPAK™ RUN LOG

The table below lists the computer runs performed for this calculation. The list includes the input, database, and output files associated with the generated results presented in this calculation. The files are contained on an optical disk that accompanies this calculation.

FLUENT™ / ICEPAK™ Run Log

Case #	Operating Condition	File Name	Date
1	Vertical enclosure w/ aspect ratio = 1.0, Pr ≈ 0.7 & Ra ≈ 10^4	CAVITY100.model CAVITY100.problem	4/3/2003 "
2	Vertical enclosure w/ aspect ratio = 1.0, Pr ≈ 0.7 & Ra ≈ 10^6	CAVITY200.model CAVITY200.problem	4/3/2003 "
3	Vertical enclosure w/ aspect ratio = 1.0, Pr ≈ 0.7 & Ra ≈ 10^8	CAVITY300.model CAVITY300.problem	4/3/2003 "
4	Vertical enclosure w/ aspect ratio = 1.0, Pr ≈ 2.0 & Ra ≈ 10^4	CAVITY400.model CAVITY400.problem	4/3/2003 "

8. SAMPLE INPUT DECKS

Pages 22 through 33 are proprietary and intentionally removed.