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# Lawrence Livermore Laboratory

THERMAL ANALYSES OF THE IF-300 SHIPPING CASK


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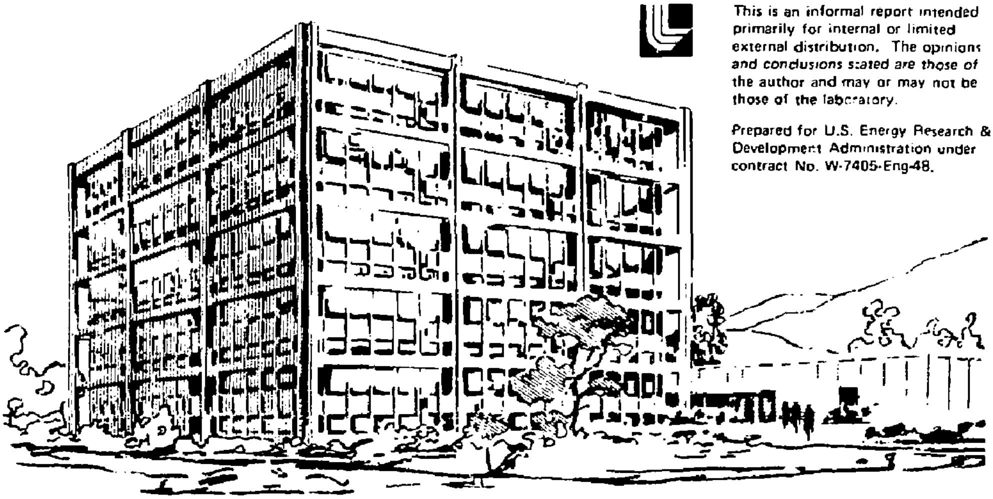




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## SUMMARY

In order to supply temperature data for structural testing and analysis of shipping casks, a series of thermal analyses using the TRUMP thermal analyzer program were performed on the GE IF-300 spent fuel shipping cask pictured in Figure 1. The results of these analyses are summarized in Table 2 and presented in more detailed form in Figures 2 through 9 and Tables 3 through 8. The location of the nodes listed in these figures and tables may be determined using Figure A1 which is a node diagram of the computer model used for these analyses. Major conclusions of these analyses are:

1. Under normal cooling conditions and a cask heat load of 262,000 BTU/hr, the seal area of the cask will be roughly 100°C (180°F) above the ambient surroundings.
2. Under these same conditions the uranium shield at the midpoint of the cask will be between 69°C (125°F) and 92°C (166°F) above the ambient surroundings.
3. Significant thermal gradients are not likely to develop between the head studs and the surrounding metal.
4. A representative time constant for the cask as a whole is on the order of one day.

## INTRODUCTION

As a part of the project to develop improved methods for structural analysis of spent fuel shipping containers a series of thermal analyses were performed on the GE IF-300 spent fuel shipping cask under the conditions specified in Ref. 1 and listed in Table 1. This shipping cask was selected as one that was representative of those that are used for shipping spent fuel. This analysis was done to obtain approximate values of temperatures and is not intended to be a comprehensive evaluation of the IF300. This program is geared at determining the likelihood of leakage of radioactive material from a shipping container subject to the accident conditions detailed in Ref. 1. The temperature profile of two areas of the shipping container are of special importance in this program.

1. The seal area is important since thermal stresses could cause improper operation of the seal.
2. The temperature of the materials in the side of the cask determines its resistance to puncture test it must pass.

In these analyses not only steady state but also transient temperature distributions were obtained for transitions from one required condition to another. A detailed description of the analytical techniques used in the analysis of the cask is presented in Appendix A. The main body of this report will concern itself with a presentation and discussion of t e results of the analysis.

DESCRIPTION OF CASK

The cask which was analyzed in its PWR configuration is shown in Figure 1. A maximum of 7 fuel assemblies with 196 rods each are contained within a water shield in the center of the cask. Surrounding this are 0.5 inches of steel, 4 inches of uranium shielding and 1.56 inches of steel. Surrounding this, approximately 6 inches of water, acting as a neutron shield, is contained by a 0.12 inch thick corrugated steel barrel. The head of the cask is covered with steel fins whose primary purpose is kinetic energy absorption in case of an accident and whose secondary role is to transfer heat from the cask. The trailer upon which the cask sits also contains fans and air distrubution ducting which provide forced air flow over the corrugated exterior of the cask. The maximum power level in the cask is 262,000 BTU/hr.

PRESENTATION OF RESULTS

A typical procedure in loading a fuel cask is as follows. The cask is placed in the water pool holding the spent fuel. The fuel assemblies are loaded into the cask. The head is placed on the cask and the cask is removed from the pool where the head is then bolted to the body of the cask. Since roughly 2 hours might be required before the cask is removed from the building housing the water pool, the first analysis performed simulates this period of time.

Figure 2 shows that, as expected, the temperatures within the cask increase due to the fuel's heat generation even though the ambient temperature surrounding the cask remains a constant 35°C (95°F). It is important to note that the stud (node 237) and the metal surrounding it (node 256) follow almost identical paths during this transient. The final temperature (+ 2 hours) reached by all the nodes in the model is presented in Table 3.

Figure 3 presents the response of the cask when it is moved into a 54.4°C (130°F) environment after the 2 hour soak period within the containment building. Note again that the heat up of the stud and metal surrounding it are almost identical. Table 4 presents the steady-state temperature distribution of the cask under the 54.4°C (130°F) soak conditions.

The response of the cask for the case of mechanical cooling failure with the cask in a 54.4°C (130°F) environment is given in Figure 4 and Table 5.

If the cask had been removed from the containment building into a -40°C (-40°F) ambient environment, the calculated response of the cask is given in Figure 5 and Table 6.

In the highly unlikely event that the case were transferred immediately from a 54.4°C (130°F) environment to a -40°C (-40°F) environment, the response of the cask is given in Figure 6.

The fire part of the accident condition requires that the case be exposed to a 801.7°C (1475°F) fire for 30 minutes. An assumption is made that the accident causes the loss of the water in the outer neutron shield of the cask. Therefore, heat is transferred between the cask barrel and the cask body by radiation and a small amount of convection in the air, rather than convection in water. Figure 7 and Table 7 show the effect of the 30 minute fire exposure on the cask originally at steady-state in a 54.4°C (130°F) environment.

After the fire, the cask must remain in a 54.4°C (130°F) environment with no artificial cooling for 3 hours. The effect of this soak on the cask during the first 20 minutes is given in Figure 8. At this time, the bulk coolant temperature of the water around the fuel reaches a sufficient value (225°C) to cause boil-off and venting of the coolant. The next 160 minutes of the 3 hours soak are then given in Figure 9 and the final temperatures reached by the cask are given in Table 8.

A summary of the steady-state temperatures of important points within the cask under the various environments analyzed is presented in Table 2. The maximum temperature reached by the region in which the seal is located is 155°C (311°F) under accident conditions. The minimum temperature of the seal region is 80°C (176°F). It should be noted that these temperatures are based on a thermal load of 262,000 BTU/hr. If the thermal load were less, the temperatures would be lower. More particularly, the temperature of the seal could approach -40°C under a very small thermal load.

A comparison of the temperatures given in Table 2 with those given in Ref. 2 shows that some of our predictions are higher. The principle reason for these differences is that we analyzed the end of the cask to which the head is bolted, whereas, in the Ref. 2 analysis, the base end of the cask was analyzed. Since the forced convection cooling does not extend as close to the head end of the cask as it does to the base end, temperatures in the head end reach higher values.

For example, the maximum temperature reached by the fuel during normal cooling in a 54.4°C environment is 209°c in our analysis, whereas, in the GE analysis the maximum fuel temperature was 158°C. Our calculated temperature for the fuel at the cask midpoint (159$^{o}$C) compares very well to the value given in the GE analysis however.

In examining Figures 2 through 7, two important conclusions may b reached: (1) the temperature of the head studs and the metal surrounding them are always almost identical. This should tend to minimize thermal stress problems, and (2) the time constant of the cask as a whole for normal hot or normal cold transition is on the order of a day. Thus, temperature changes within the cask take place very slowly.

TABLE 1

CASK OPERATING CONDITIONS

| OPERATING CONDITION | AMBIENT TEMPERATURE |
|---|---|
| *Post Loading (no fans) | 35°C (95°F) for 2 hours |
| Normal Hot (w/fans) | 54.4°C (130°F) |
| Normal Cold (w/fans) | -40°C (-40°F) |
| Accident (no fans) | 801.7°C (1475°F) for 30 minutes |
| | + 3 hour soak @ 54.4°C (130°F) |

*Not in Reference 1 but typical of cask loading routine.

TABLE 2 - SUMMARY OF CASK TEMPERATURES IN °C

| | Node Number | | 2 hour Soak at 35°C No Mechanical Cooling | Normal Cooling at 54.4°C | Loss of Mechanical Cooling at 54.4°C | Normal Cooling at -40°C | FIRE - 30 Minutes at 801.7°C | 3 Hours Soak at 54.4°C After Fire |
|---|---|---|---|---|---|---|---|---|
| | 88 | Seal Area | 48. | 155. | 169. | 81. | 282. | 206. |
| | 237 | Ave. Head Stud | 42. | 135. | 145. | 57. | 311. | 184. |
| | 1 | Neutron Shield Containment | 39. | 95. | 201. | 3. | 682. | 124. |
| Cask Midpoint Temperature (°C) | 41 | Neutron Shield Water | 40. | 104. | 209. | 18. | * | * |
| | 61 | Outer Steel Shell | 46. | 118. | 223. | 40. | 300. | 212. |
| | 81 | Uranium Shield | 52. | 133 | 237. | 57. | 227. | 217. |
| | 101 | Inner Steel Shell | 59. | 147. | 249. | 72. | 191. | 222. |
| | 121 | Inner Water Shield | 63. | 154. | 256. | 82. | 174. | 225. |
| | 141 | Fuel | 67. | 159 | 261. | 87. | 175. | 228. |
| Normal Hot Spot Temperature (°C) | 4 | Neutron Shield Containment | 39. | 99. | 198. | 7. | 683. | 125. |
| | 44 | Neuton Shield Water | 41. | 108. | 206. | 24. | * | * |
| | 65 | Outer Steel Shell | 52. | 177. | 208. | 104. | 247. | 211. |
| | 85 | Uranium Shield | 55. | 186. | 216. | 114. | 220. | 217. |
| | 105 | Inner Steel Shell | 60. | 197. | 228. | 126. | 214. | 222. |
| | 125 | Inner Water Shield | 64. | 204. | 235. | 136. | 210. | 225. |
| | 145 | Fuel | 68. | 209. | 240. | 141. | 214. | 228. |

*Shield Water Lost

Detail of Stud

| 41.9 256S | | |
|---|---|---|
| 40.7 236S | 41.8 237S | 43.4 238S |

← Stud →

| (COLUMN 1) | FINS | HEAD | | | UNCOOLED BODY | | | | COOLED BODY | | | | (COLUMN 4) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.7 | | 49.1 | 49.4 | 52.3 | 55.2 | 65.5 | 67.2 | 67.6 | 66.6 | 66.6 | 66.6 | 66.6 | 19.7 | INNER WATER SHIELD |
| 27.9 | 39.7 | 46.5 | 48.9 | 52.6 | 56.2 | 66.1 | 67.9 | 68.3 | 67.2 | 67.2 | 67.2 | 67.2 | 8.24 | FUEL |
| 47.6 | 38.6 | 44.4 | 46.6 | 49.5 | 52.5 | 62.2 | 63.9 | 64.3 | 63.1 | 63.1 | 63.1 | 63.1 | 19.7 | INNER WATER SHIELD |
| 48.9 | 37.7 | 41.8 | 44.2 | 46.4 | 50.3 | 58.1 | 60.0 | 60.4 | 58.6 | 58.6 | 58.6 | 58.6 | 1.27 | SS INNER SHELL |
| 59.1 | 37.4 | 40.3 | | 44.5 | 47.6 | 52.3 | 54.4 | 55.0 | 51.8 | 51.8 | 51.8 | 51.8 | 10.16 | URANIUM SHIELD |
| 63.0 | 36.9 | 39.1 | 40.4 | 42.7 | 45.5 | 49.4 | 51.2 | 51.5 | 45.6 | 45.6 | 45.6 | 45.6 | 3.96 | S.S. OUTER SHELL |
| 70.7 | 36.5 | 36.9 FINS | 37.1 FINS | | 41.5 | | | | 40.5 | 40.4 | 40.[illegible] | 40.4 | 7.7 | NEUTRON SHIELD |
| 78.4 | | | | | 37.3 | | | | 40.2 | 40.2 | 40.2 | 40.2 | 7.7 | WATER |
| 78.7 | | | | | | | | | 39.0 | 39.0 | 39.0 | 39.0 | .3 | NEUTRON SHIELD WATER CONTAINMENT |
| | 24.2 | 5.12 | 7.68 | 2.56 | 9.86 | 9.86 | 9.86 | 9.86 | 34.4 | 39.4 | 39.4 | 39.4 | (COLUMN 2) | |

TEMPERATURE OF THE CASK (2 hrs at 35°C) TEMPERATURE IN °C

DIMENSIONS IN CM

TABLE 3

Detail of Stud Area

| Stud | | |
|---|---|---|
| 134.8 | | |
| 127.9 | 134.7 | 141.4 |

| (COLUMN 1) | FINS | HEAD | | | UNCOOLED BODY | | | | COOLED BODY | | | | (COLUMN 4) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.7 | | 150.6 | 151.3 | 156.8 | 161.5 | 195.0 | 207.0 | 209.0 | 165.6 | 160.2 | 159.1 | 158.9 | 19.7 | INNER WATER SHIELD |
| 27.9 | 93.0 | 111.9 | 149.7 | 156.6 | 162.4 | 195.1 | 207.1 | 209.6 | 165.6 | 160.2 | 159.1 | 158.9 | 8.24 | FUEL |
| 47.6 | 86.9 | 137.9 | 145.9 | 152.8 | 158.4 | 190.8 | 202.5 | 204.3 | 160.7 | 155.4 | 154.3 | 154.1 | 19.7 | INNER WATER SHIELD |
| 48.9 | 80.3 | 129.3 | 140.4 | 147.8 | 157.0 | 184.2 | 195.4 | 197.1 | 153.1 | 147.8 | 146.7 | 146.5 | 1.27 | SS INNER SHELL |
| 59.1 | 80.1 | 124.5 | 134.8 | 144.9 | 155.1 | 173.8 | 184.0 | 185.8 | 139.6 | 133.4 | 133.4 | 133.2 | 10.16 | URANIUM SHIELD |
| 63.0 | 77.7 | 116.3 | 125.8 | 136.7 | 149.4 | 167.6 | 176.6 | 176.5 | 123.3 | 118.5 | 117.7 | 117.5 | 3.96 | S.S. OUTER SHELL |
| 70.7 | 79.1 | 98.2 | 103.7 | | 139.0 | | | | 108.2 | 104.4 | 103.7 | 103.6 | 7.7 | NEUTRON SHIELD WATER |
| 78.4 | | | | | 119.1 | | | | 106.9 | 103.2 | 102.5 | 102.4 | 7.7 | |
| 78.7 | | | | | | | | | 98.7 | 95.5 | 94.9 | 94.8 | .3 | NEUTRON SHIELD WATER CONTAINMENT |
| | | | | | | | | | | | | | (COLUMN 2) | |

TEMPERATURE OF THE CASKS
(S.S. at 54.4°C)
TEMPERATURE IN °C
DIMENSIONS IN CM
TABLE 4

Detail of Stud Area

| | | |
|---|---|---|
| 145.4 | | |
| 137.5 | 145.4 | 153.1 |
| ← | Stud | → |

| Column 1 (cm) | FINS | HEAD | | | UNCOOLED BODY | | | | COOLED BODY | | | | Column 4 (cm) | Layer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.7 | | 161.5 | 162.3 | 168.5 | 173.5 | 213.3 | 230.9 | 239.6 | 257.5 | 260.0 | 260.7 | 261.0 | 19.7 | INNER WATER SHIELD |
| 27.9 | 97.2 | 152.1 | 160.7 | 168.4 | 174.6 | 213.3 | 230.9 | 239.6 | 257.5 | 260.0 | 260.7 | 261.0 | 8.24 | FUEL |
| 47.6 | 90.4 | 148.6 | 156.9 | 164.5 | 170.6 | 209.1 | 226.3 | 235.0 | 252.6 | 255.2 | 255.9 | 256.1 | 19.7 | INNER WATER SHIELD |
| 48.9 | 83.2 | 138.7 | 151.2 | 159.8 | 170.1 | 202.5 | 219.2 | 227.8 | 245.3 | 247.8 | 248.5 | 248.7 | 1.27 | SS INNER SHELL |
| 59.1 | 83.0 | 133.6 | 145.4 | 157.3 | 169.1 | 192.4 | 207.9 | 216.2 | 233.3 | 235.8 | 236.5 | 236.8 | 10.16 | URANIUM SHIELD |
| 63.0 | 80.2 | 124.3 | 135.2 | 148.0 | 163.0 | 185.7 | 199.7 | 207.5 | 219.5 | 221.8 | 222.5 | 222.7 | 3.96 | S.S. OUTER SHELL |
| 70.7 | 81.9 | 103.7 | 110.0 | | 154.1 | | | | 206.4 | 208.5 | 209.2 | 209.4 | 7.7 | NEUTRON SHIELD WATER |
| 78.4 | | | | | 129.9 | | | | 205.3 | 207.4 | 208.0 | 208.2 | 7.7 | |
| 78.7 | | | | | | | | | 197.9 | 199.8 | 200.4 | 200.6 | .3 | NEUTRON SHIELD WATER CONTAINMENT |

(COLUMN 1) (COLUMN 2) (COLUMN 4)

TEMPERATURE OF THE CASK
(S.S. at 54.4°C with no mechanical cooling)
TEMPERATURES IN °C
DIMENSIONS IN CM

TABLE 5

Detail of Stud Area

| | | |
|---|---|---|
| 57.7 | | |
| 49.4 | 57.3 | 65.1 |
| Stud | | |

| (COLUMN 1) | FINS | HEAD | | | UNCOOLED BODY | | | | COOLED BODY | | | | (COLUMN 4) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.7 | | 76.1 | 76.7 | 82.3 | 88.4 | 125.2 | 138.5 | 140.7 | 95.1 | 88.9 | 87.5 | 87.3 | 19.7 | INNER WATER SHIELD |
| 27.9 | 5.0 | 64.8 | 73.9 | 81.4 | 89.3 | 125.3 | 138.5 | 140.8 | 95.1 | 88.9 | 87.5 | 87.3 | 8.24 | FUEL |
| 47.6 | -1.9 | 60.4 | 69.5 | 77.2 | 85.0 | 120.9 | 133.8 | 135.9 | 90.0 | 83.8 | 82.5 | 82.2 | 19.7 | INNER WATER SHIELD |
| 48.9 | -9.8 | 50.7 | 63.5 | 72.1 | 82.9 | 111.7 | 123.9 | 125.8 | 79.4 | 73.2 | 71.9 | 71.6 | 1.27 | SS INNER SHELL |
| 59.1 | -9.7 | 45.5 | 57.5 | 69.3 | 80.9 | 100.8 | 111.7 | 113.7 | 64.9 | 58.8 | 57.5 | 57.3 | 10.16 | URANIUM SHIELD |
| 63.0 | -11.9 | 36.4 | 47.8 | 60.8 | 75.6 | 94.2 | 103.7 | 103.6 | 47.4 | 41.7 | 40.6 | 40.4 | 3.96 | S.S. OUTER SHELL |
| 70.7 | -7.9 | 15.9 | 22.7 | | 65.0 | | | | 23.6 | 19.4 | 18.5 | 18.3 | 7.7 | NEUTRON SHIELD WATER |
| 78.4 | | | | | 48.5 | | | | 22.1 | 18.0 | 17.2 | 17.0 | 7.7 | |
| 78.7 | | | | | | | | | 6.8 | 3.6 | 2.9 | 2.8 | .3 | NEUTRON SHIELD WATER CONTAINMENT |
| | | | | | | | | | | | | | (COLUMN 2) | |

TEMPERATURE OF THE CASK
(S.S. AT -40°C)
TEMPERATURE IN °C
DIMENSIONS IN CM

TABLE 6

Stud Detail Area

| 314.0 | | |
|---|---|---|
| 361.2 | 311.3 | 289.8 |

← Stud →

(COLUMN 1) | FINS | HEAD | UNCOOLED BODY | COOLED BODY | (COLUMN 4)

| (COLUMN 1) | FINS | HEAD | | | UNCOOLED BODY | | | | COOLED BODY | | | | (COLUMN 2) | (COLUMN 4) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.7 | | 338.3 | 320.7 | 251.3 | 215.6 | 202.7 | 210.6 | 212.3 | 177.8 | 172.4 | 171.3 | 171.1 | 19.7 | INNER WATER SHIELD |
| 27.9 | 651.0 | 319.3 | 263.6 | 230.2 | 214.8 | 205.3 | 212.0 | 213.5 | 181.4 | 176.1 | 175.0 | 174.8 | 8.24 | FUEL |
| 47.6 | 699.3 | 325.8 | 254.2 | 223.9 | 210.6 | 203.1 | 208.9 | 210.2 | 181.0 | 175.7 | 174.6 | 174.4 | 19.7 | INNER WATER SHIELD |
| 48.9 | 718.2 | 368.0 | 280.7 | 259.6 | 232.4 | 214.0 | 213.4 | 213.5 | 197.4 | 192.3 | 191.2 | 191.0 | 1.27 | SS INNER SHELL |
| 59.1 | 720.8 | 399.7 | 314.0 | 292.9 | 282.2 | 235.5 | 221.7 | 219.9 | 232.7 | 228.5 | 227.3 | 227.1 | 10.16 | URANIUM SHIELD |
| 63.0 | 742.6 | 498.6 | 433.0 | 430.1 | 404.7 | 268.8 | 247.1 | 247.0 | 304.2 | 300.9 | 299.9 | 299.7 | 3.96 | S.S. OUTER SHELL |
| 70.7 | 768.9 | 611.6 | 559.1 | | 475.8 | | | | | | | | 7.7 | NEUTRON SHIELD WATER |
| 78.4 | | | | | 658.0 | | | | | | | | 7.7 | |
| 78.7 | | | | | | | | | 682.6 | 682.2 | 682.1 | 682.1 | .3 | NEUTRON SHIELD WATER CONTAINMENT |

TEMPERATURE OF THE CASK
(30 minutes at 801.7°C)

TEMPERATURE IN °C
DIMENSIONS IN CM

TABLE 7

Detail of Stud Area

| | | |
|---|---|---|
| 183.9 | | |
| 174.0 | 182.9 | 191.1 |
| Stud | | |

| (COLUMN 1) | FINS | HEAD | | | UNCOOLED BODY | | | | COOLED BODY | | | | (COLUMN 4) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.7 | | 208.7 | 210.0 | 218.7 | 225.4 | 225.4 | 225.4 | 225.4 | 225.4 | 225.4 | 225.4 | 225.4 | 19.7 | INNER WATER SHIELD |
| 27.9 | 115.6 | 196.7 | 208.9 | 219.2 | 227.2 | 228.1 | 228.0 | 228.0 | 227.9 | 227.9 | 227.9 | 227.9 | 8.24 | FUEL |
| 47.6 | 105.9 | 192.6 | 204.8 | 216.3 | 225.3 | 225.3 | 225.2 | 225.1 | 225.1 | 225.0 | 225.1 | 225.0 | 19.7 | INNER WATER SHIELD |
| 48.9 | 95.1 | 177.4 | 194.5 | 203.7 | 217.7 | 220.4 | 221.3 | 221.6 | 221.8 | 221.7 | 221.7 | 221.7 | 1.27 | SS INNER SHELL |
| 59.1 | 95.0 | 169.1 | 183.9 | 195.1 | 205.6 | 213.0 | 215.9 | 216.8 | 217.5 | 217.3 | 217.3 | 217.2 | 10.16 | URANIUM SHIELD |
| 63.0 | 91.6 | 156.6 | 170.2 | 182.2 | 195.5 | 207.0 | 210.3 | 211.3 | 212.4 | 212.3 | 212.2 | 212.1 | 3.96 | S.S. OUTER SHELL |
| 70.7 | 95.5 | 131.2 | 140.9 | | 177.2 | | | | | | | | 7.7 | NEUTRON SHIELD WATER |
| 78.4 | | | | | 160.5 | | | | | | | | 7.7 | |
| 78.7 | | | | | | | | | 124.6 | 124.5 | 124.5 | 124.4 | .3 | NEUTRON SHIELD WATER CONTAINMENT |
| | | | | | | | | | | | | | (COLUMN 2) | |

TEMPERATURE OF THE CASK
(3 HRS after fire in 544°C air)
TEMPERATURE IN °C
DIMENSIONS IN CM

TABLE 8

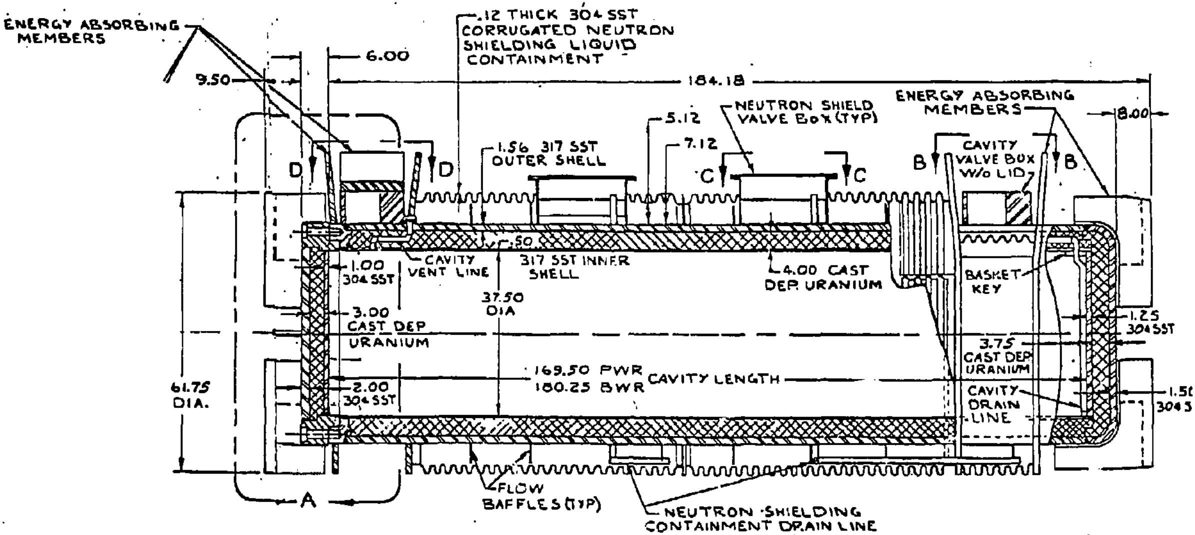



FIGURE 1. SECTIONAL VIEW OF CASK WITH PWR CASK HEAD

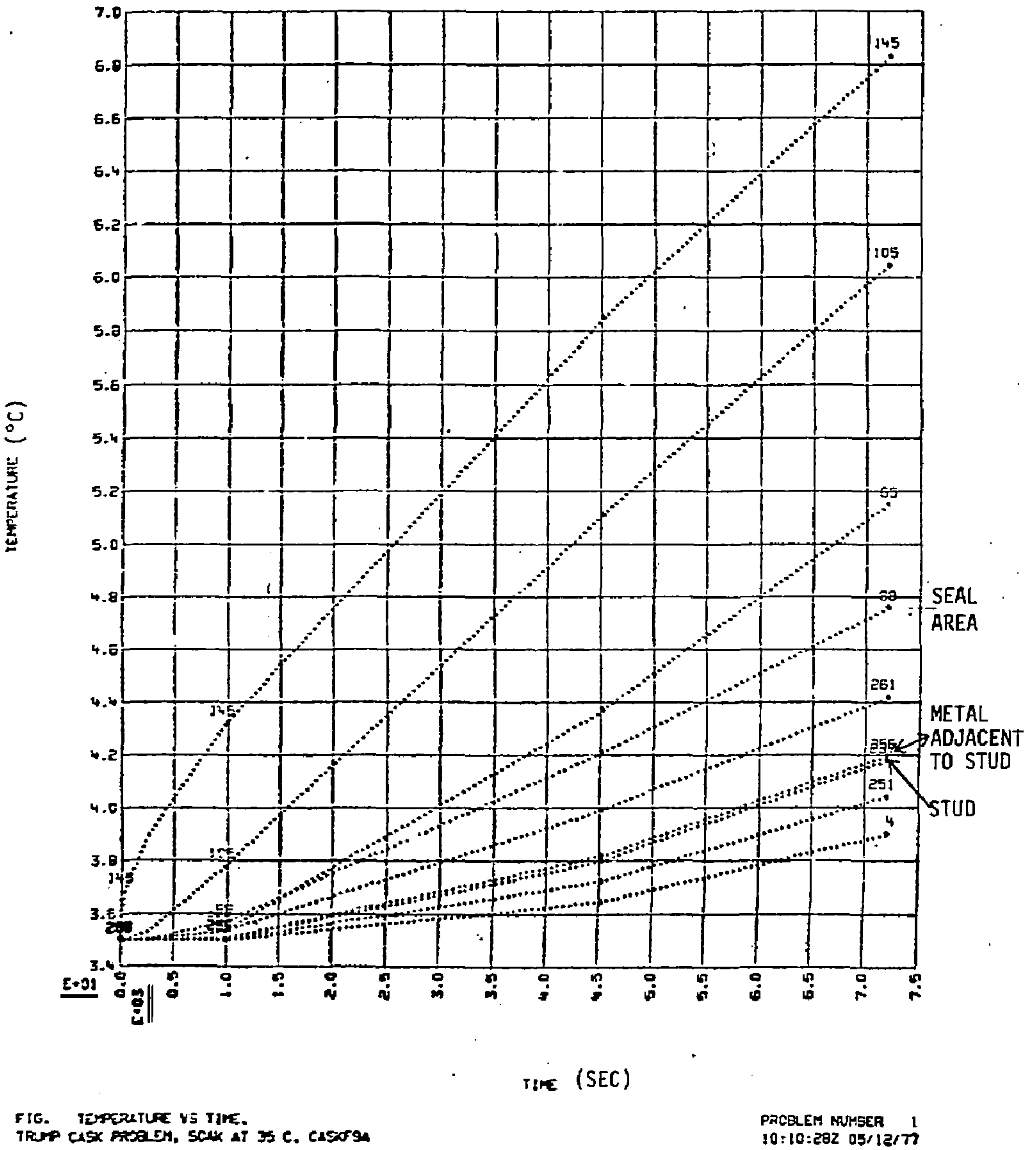



FIGURE 2. HEAT UP OF CASK INSIDE BUILDING

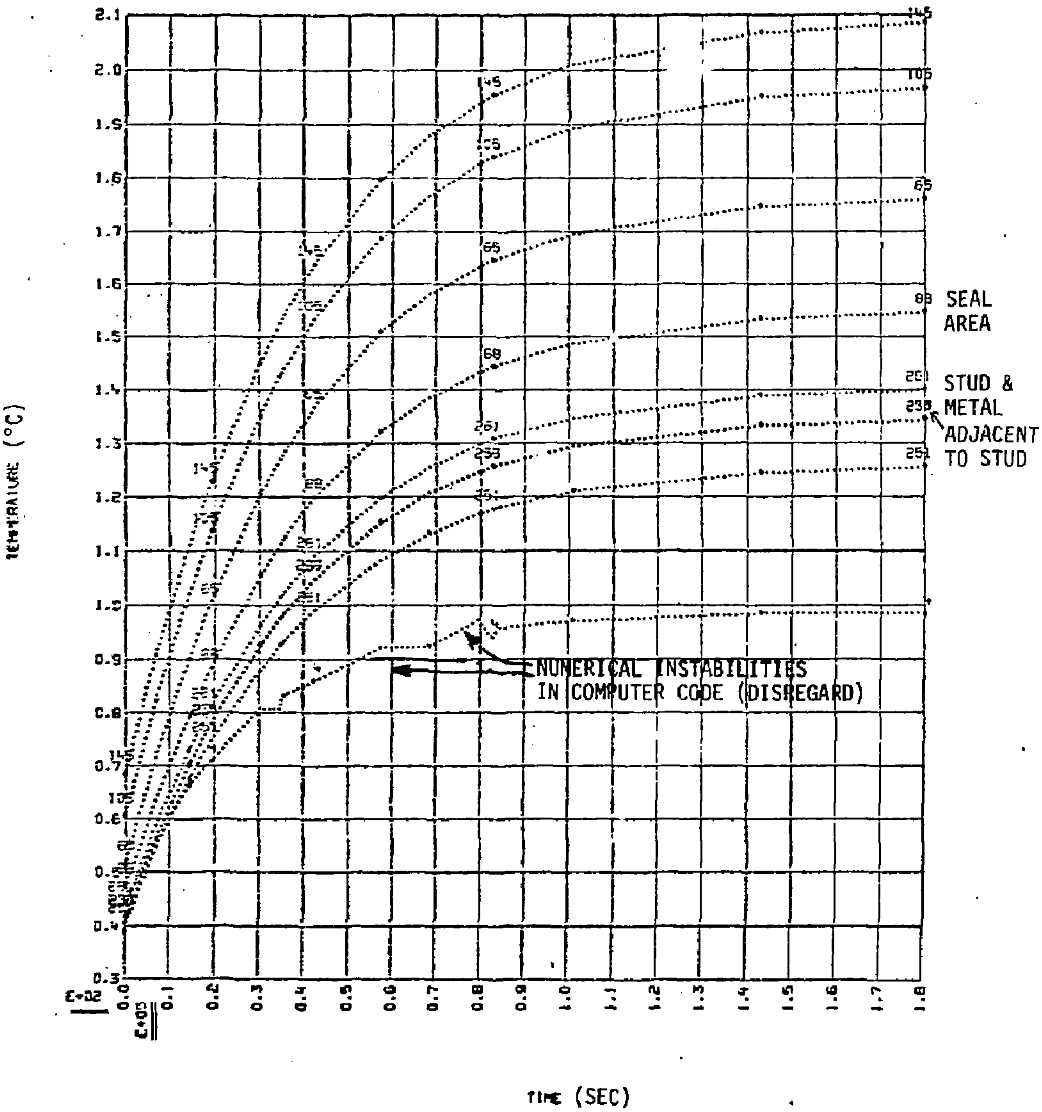



FIG. TEMPERATURE VS TIME.
TRUMP CASK PROBLEM, SOAK AT 54.4 C, CASKF9C

PROBLEM NUMBER 1
10:23:002 05/12/77

FIGURE 3. HEAT UP OF CASK IN 54.4°C AMBIENT

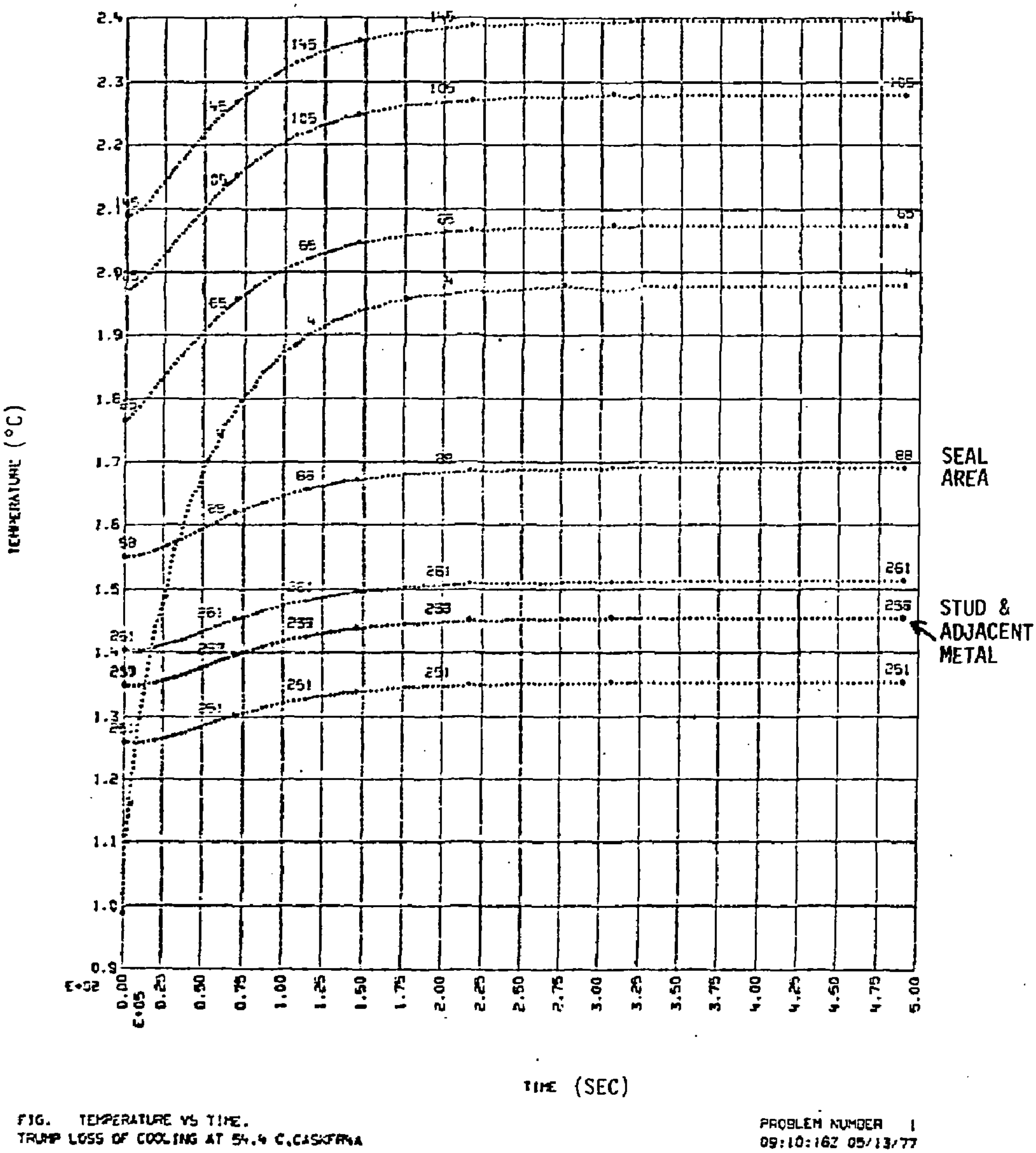



FIGURE 4. HEAT UP OF CASK AFTER LOSS OF MECHANICAL COOLING (@ 54.4°C)

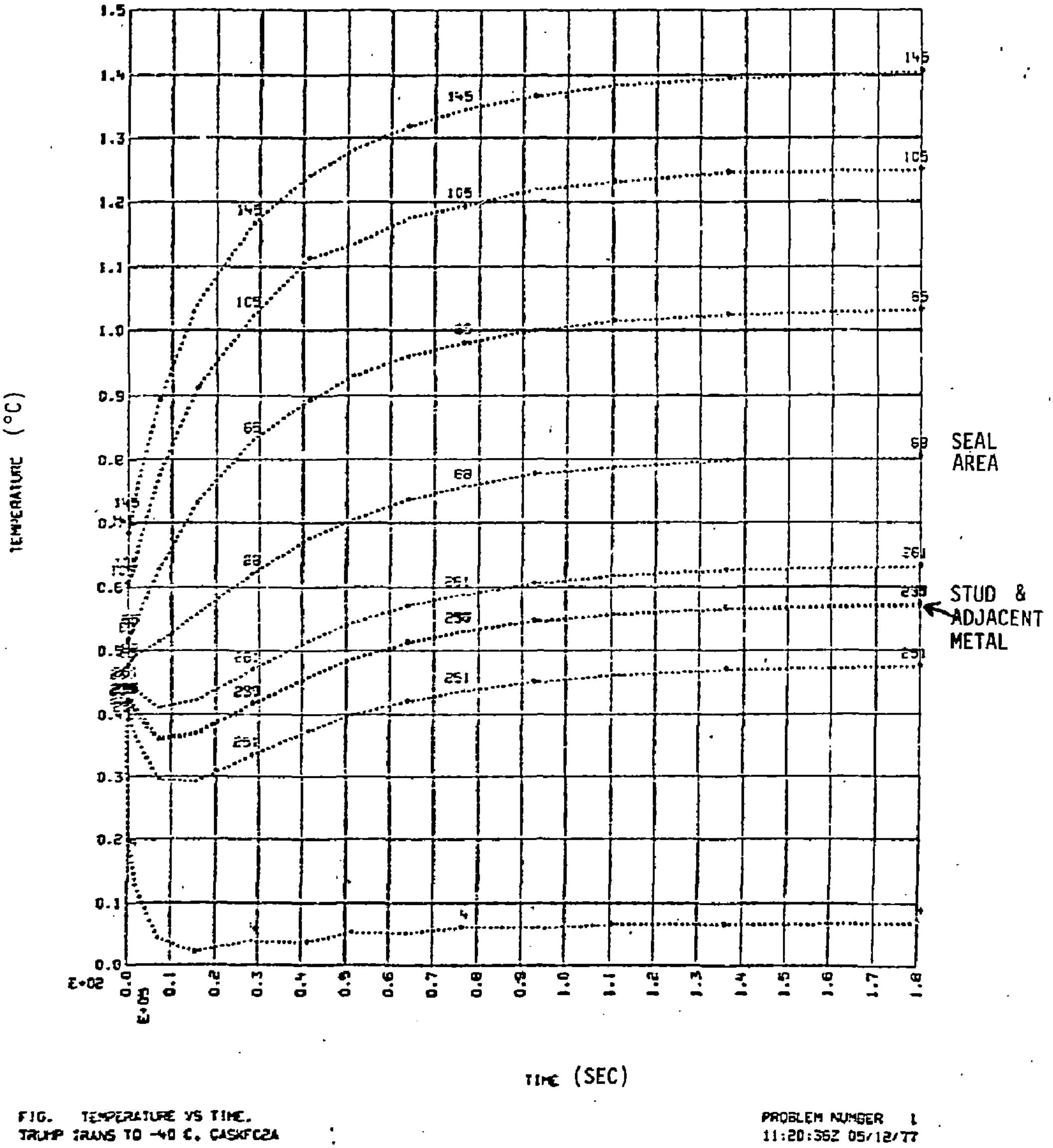



FIGURE 5 TRANSITION TO -40°C AMBIENT

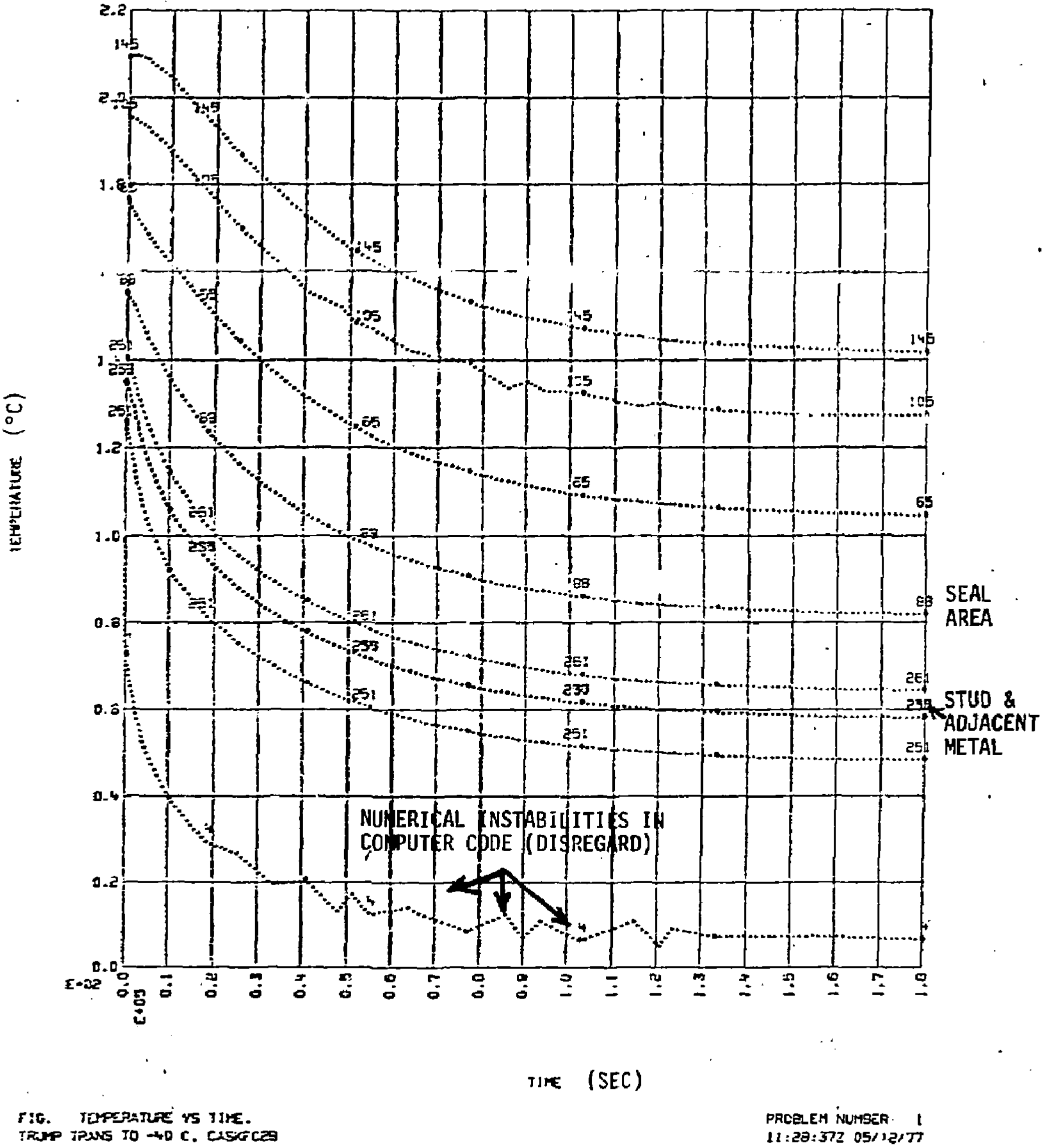



FIGURE 6. TRANSITION FROM 54.4°C to-40°C AMBIENT

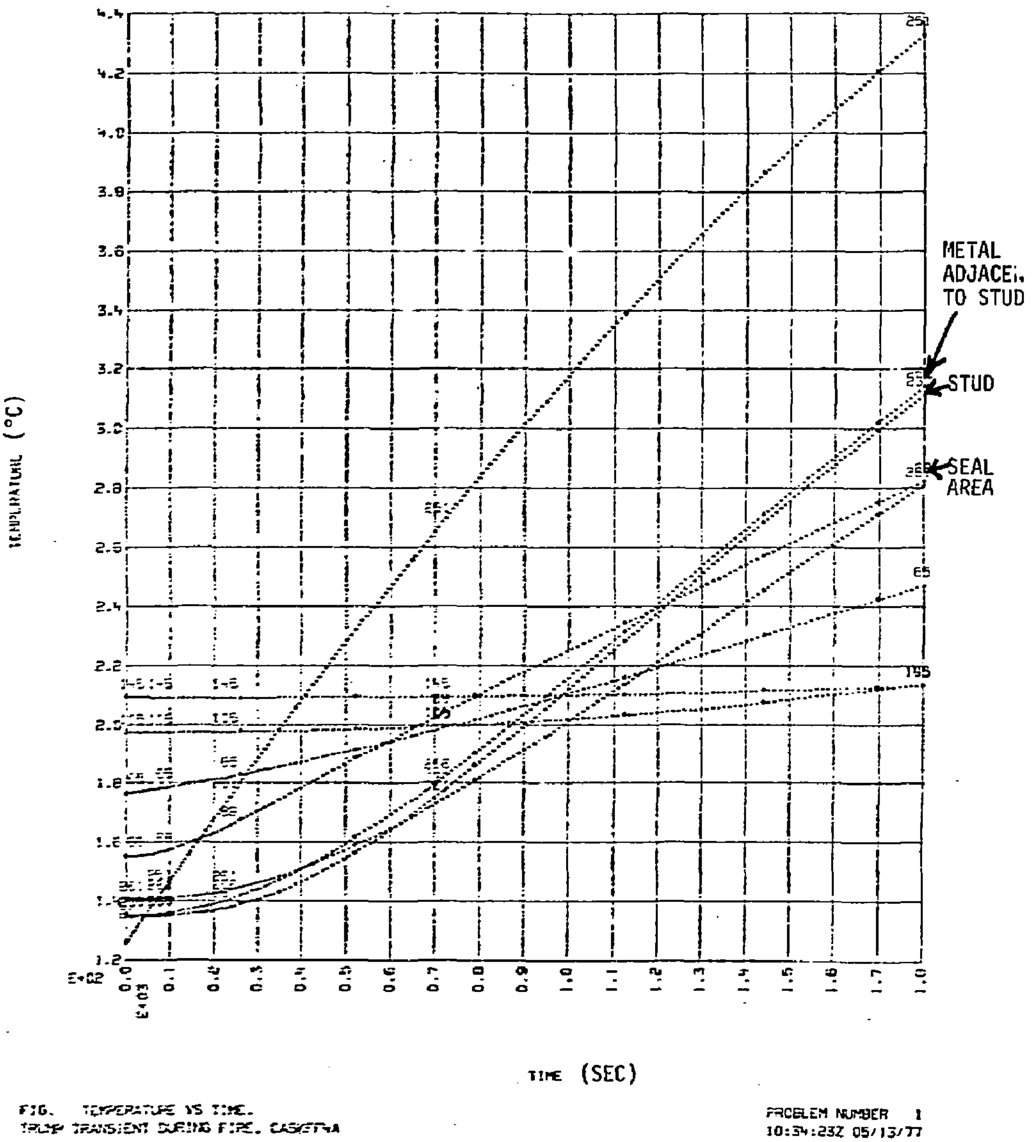



FIGURE 7. TRANSIENT DURING FIRE

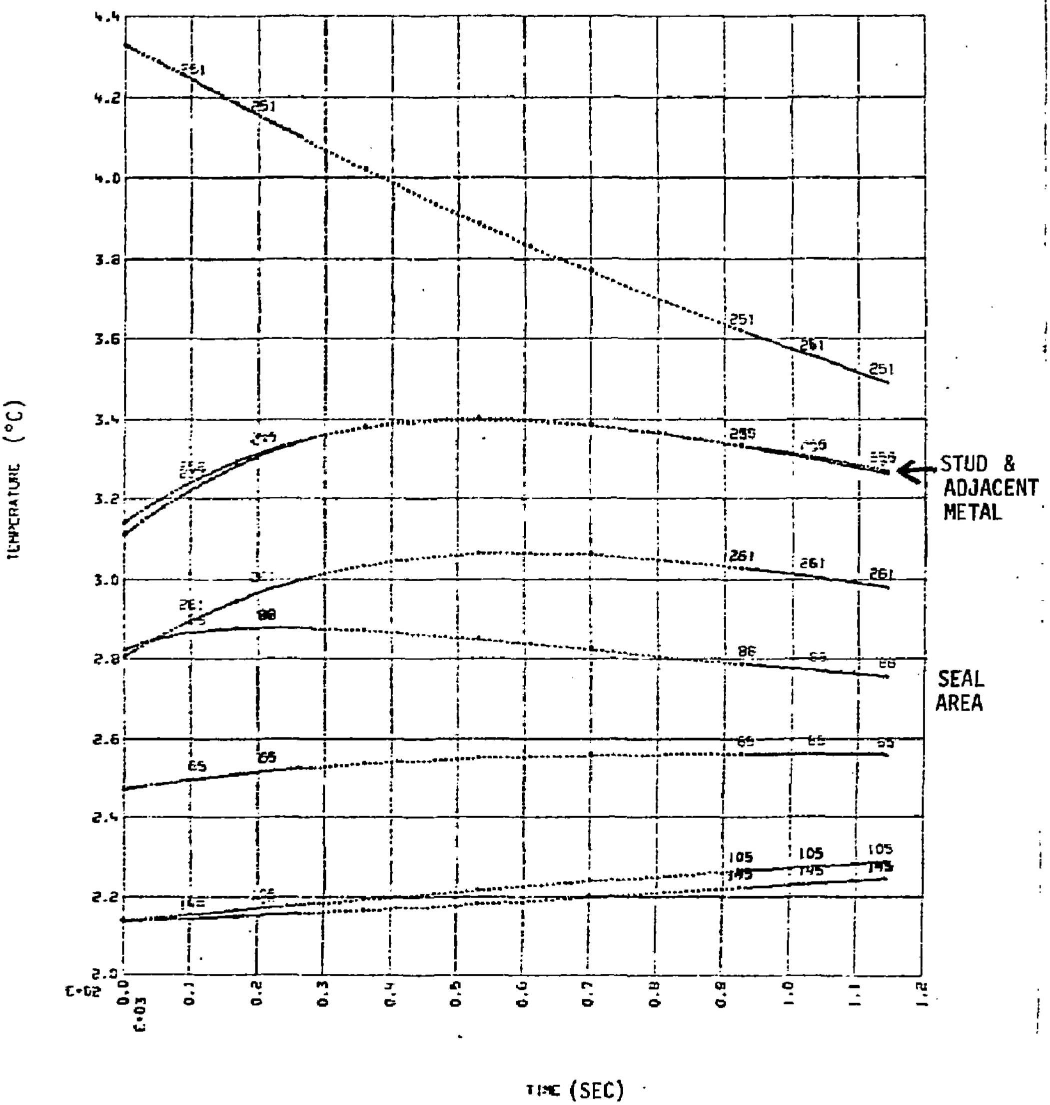



FIG. TEMPERATURE VS TIME.
TRUMP TRANSIENT AFTER FIRE. CASKFF40.

PROBLEM NUMBER 1
14:08:03Z 05/24/77

FIGURE 8. FIRST 20 MINUTES OF SOAK AFTER THE FIRE

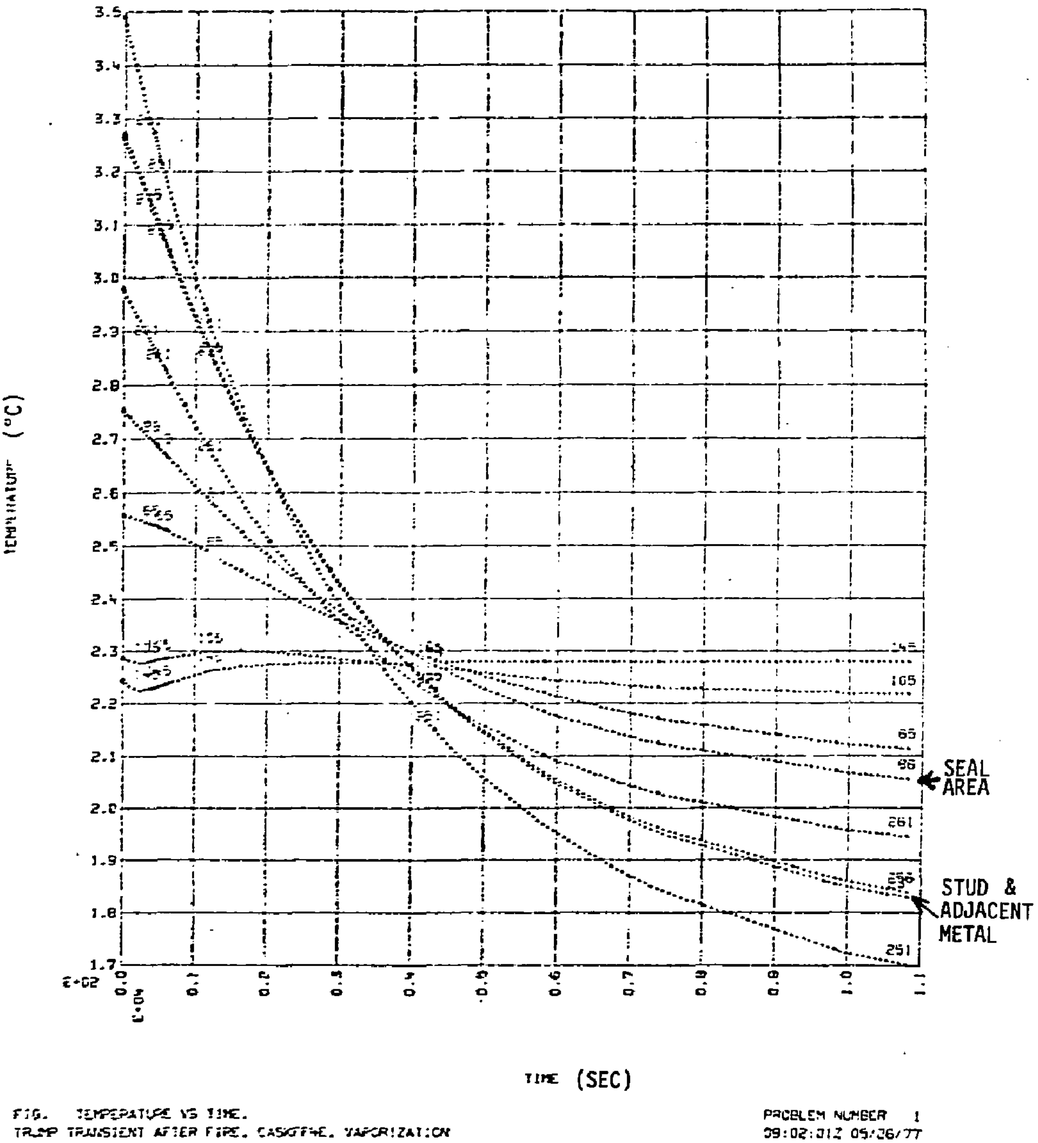



FIGURE 9. SOAK AFTER FIRE ( 20 MINUTES→ 3 HOURS)

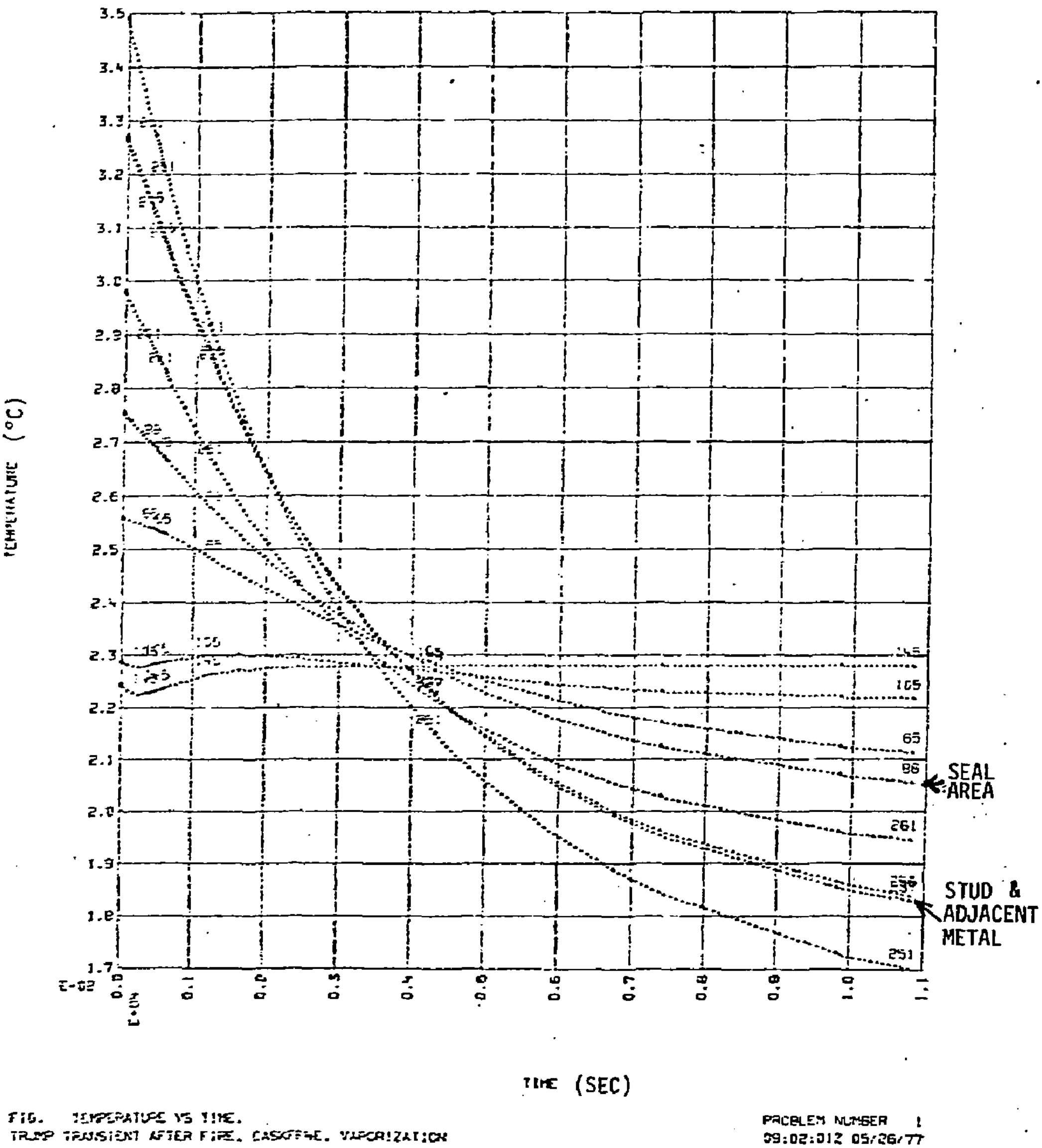



FIGURE 9. SOAK AFTER FIRE ( 20 MINUTES→ 3 HOURS)

## REFERENCES


1. United States Regulatory Commission, Rules and Regulations, Title 10 Chapter 1, Code of Federal Regulations - Energy Part 71 "Packaging of Radioactive Material for Transport and Transportation of Radioactive Materials Under Certain Conditions" Appendices A & B.

2. General Electric Nuclear Fuel Department, "Design and Analysis Report IF-300 Shipping Cask," NEDO-10084-1, February 1973.

3. Glasstone & Sesonske, "Nuclear Reactor Engineering," D. Van Nostrand Company, Inc., Princeton, New Jersey, 1963.

4. Kreith, F., "Principles of Heat Transfer," International Textbook Company, Scranton, Pennsylvania, 1960.

5. Edwards, A. L., "TRUMP: A Computer Program for Transient and Steady-State Temperature Distributions in Multi-dimensional Systems," UCRL-14754, Rev. 3, (Lawrence Livermore Laboratory, Livermore California, September 1, 1972).

# APPENDIX A

# ANALYTICAL TECHNIQUE

## SYMBOL LIST

| | | |
|---|---|---|
| $1.356 \times 10^{-4}$ | = | conversion factor between $\frac{BTU}{FT^2\text{-}HR\text{-}°F}$ and $\frac{CAL}{Cm^2\text{-}sec\text{-}°C}$ |
| b | = | spacing between outer shell and neutron shield containment |
| D | = | diameter of cask |
| g | = | gravity constant |
| Gr | = | Grashof number |
| hc | = | convection heat transfer coefficient |
| K | = | artificial conductivity used in Ref. 2. |
| Km | = | materi.l conductivity |
| L | = | length of flow path in free convection |
| Nu | = | Nusselt number |
| PA | = | total perimeter of annulus representing the fuel |
| PR | = | combined perimeter of the fuel rods |
| Pr | - | Prandtl number |
| Ta | = | temperature of the air |
| Tw | = | temperature of the water |
| X | = | length of the vertical plate |
| $\beta$ | = | temperature coefficient of volume expansion |
| $\Delta T$ | = | delta temperature |
| $\rho$ | = | mass density |
| $\pi$ | = | 3.14 |
| $\theta$ | = | angle of plate from the vertical |
| $\mu$ | = | absolute viscosity |

GENERAL

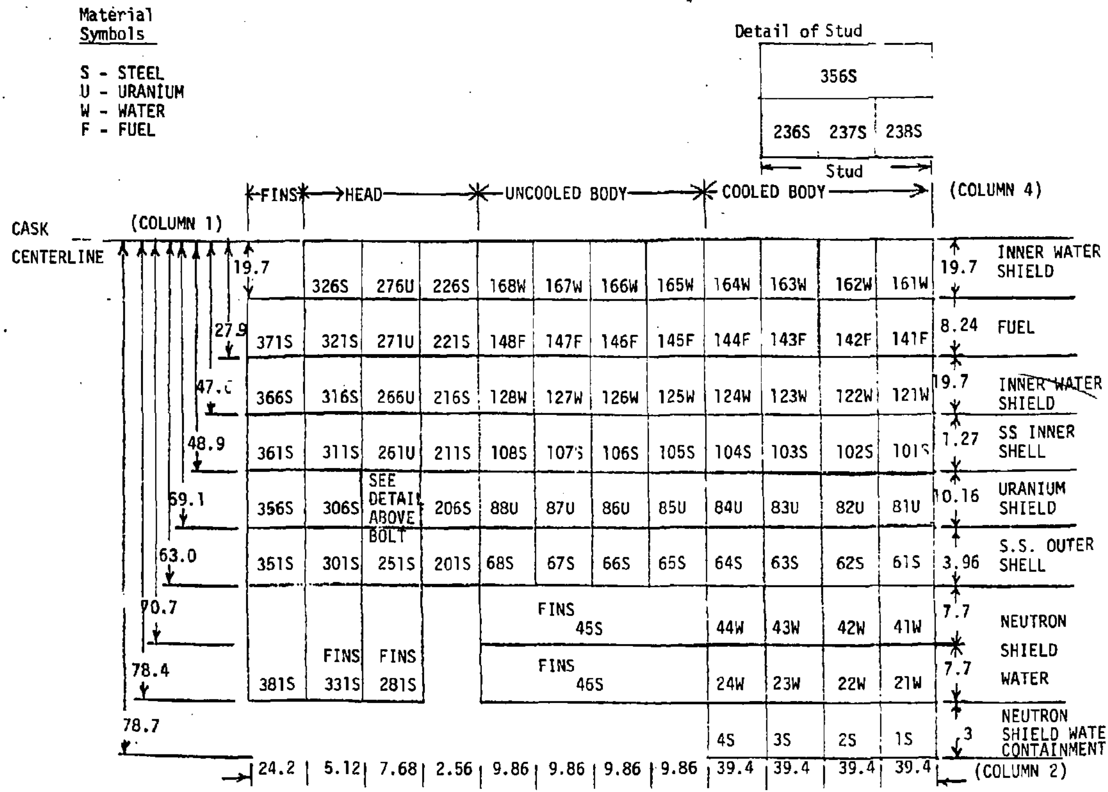
The approach taken in this analysis was to construct a TRUMP[5] thermal analyser model of the cask. The model was then used to simulate the reponse of the shipping cask to various required environmental conditions. Figure A1 is a node diagram of the model. Due to the large differences in thickness of the various materials used in the model no attempt was made to maintain a common scale in drawing Figure 2. However, the dimensions given at the side and bottom of the diagram apply to all of the nodes in that row or column. Thus node 256 has an inner radius of 48.9 cm as does node 81. A detailed description of the TRUMP Program may be found in Reference 5.

Material properties given in Reference 2 were compared to those given in Reference 3. Since differences were insignificant those given in Reference 2 were used. They are listed in Table A1.

Thermal radiation heat transfer coefficients used in the model were based on the projected area of the cask body and head with appropriate increases made to thermal emissivity values. In other words, the effect of the fins or corregations on radiation heat transfer, as calculated by the model, was to increase the emissivity of a node not to increase the area radiating.

GEOMETRY

The dimensions inputed into the cask program are those given in Figure A1 with the following exceptions. Rather than model the entire cask a, 1/8 pie shaped segment of the cask was modeled. This required dividing certain of the dimension in the model by 8. For instance the length of some of the nodes as input into the progam for use in calculation of node volume was divided by 8.




DIMENSIONS IN CM

FIGURE A1 TRUMP NODE DIAGRAM OF PWR CASK

**STEEL**

Specific Gravity = 7.84          Specific Heat = .12 CAL/GM-°C

| Temperature (°C) | 37.8 | 149. | 260. |
|---|---|---|---|
| Conductivity (CAL/CM-SEC-°C) | .00142 | .03514 | .0397 |

**URANIUM**

Specific Gravity = 19.29

| Temperature (°C) | 24.0 | 37.8 | 149.0 | 260.0 |
|---|---|---|---|---|
| Specific Heat (CAL/GR-°C) | .028 | --- | --- | .033 |
| Conductivity (CAL/CM-SEC-°C) | --- | .05912 | .06573 | .07400 |

**WATER**

Specific Gravity = 1.0

| Temperature (°C) | 0.0 | 21. | 93. | 500. |
|---|---|---|---|---|
| Specific Heat (CAL/GR-°C) | 1.01 | .998 | 1.0 | 1.08 |
| Conductivity (CAL/CM-SEC-°C) | .00132 | .00143 | .00163 | .00158 |

**FUEL**

Specific Gravity = 6.9

Specific Heat = .085 CAL/GM-°C

Conductivity = .021 CAL/CM-SEC-°C

TABLE A1

MATERIAL PROPERTIES

It should also be noted that the program allows use of different geometries in inputing the data. Those nodes associated in the listing of the model (App. B) with the word asymmetric have the value of $D_{rad}$ multiplied by $2\pi$ while those associated with the word "rectangular" are multiplied by 1.

Nodes - 141 → 321

The fuel was assumed to be concentrated in an annulus 23.82 cm. from the center of the cask. There are 7 (14 x 14) fuel rod assemblies with an individual rod area of .8992 $cm^2$ for a total of 1234 $cm^2$ in cross-sectional area. If $D_{rad}$ = 23.82 then

$$D_{WIDE} = \frac{1234}{2 \times \pi \times 23.82} = 8.24 \text{ cm}$$

CALCULATION OF CONVECTION HEAT TRANSFER COEFFICIENTS

Note that the TRUMP computer program allows a delta temperature dependence for the heat transfer coefficient. Thus in the calculations presented below the heat transfer coefficient is first calculated using an arbitrary delta temperature and then the influence of delta temperature is factored out. This resulting value along with the power of delta temperature upon which the heat transfer coefficient depends are then input into the TRUMP program.

The value of the heat transfer coefficient between the outer shell (nodes 61 through 64) and the neutron shielding liquid containment (nodes 1 through 4) was calculated using (Eq. 6.10) from Ref. 2, and Equation (7-36) from Reference 4. Since both gave similar results and the correlation given in Reference 2 was based on a configuration more nearly matching the cask, Eq. 6.10 was used.

CONVECTION IN WATER

OUTER CHAMBER (Nodes 1 → 4 to 21 → 24 and 41 → 44 to 61 → 64)

Assume

$Tw \simeq 107^{o}C \simeq 225^{o}F$

$\Delta T = 40^{o}F = 22.2^{o}C$

Let b = 5.0 inches = .417 ft

Using eq. (6.10) from Reference 2 ,

$$hc = \frac{K}{b} = \frac{.135Km}{b}\left(\frac{Pr^2Gr}{1.36+Pr}\right)^{.278}$$

$$Gr = \frac{g\beta\rho^2}{\mu^2} \times \Delta T \times b^3 = 1.63 \times 10^9 \times 40 \times .417^3 = 4.716 \times 10^9$$

$$hc = \frac{.135 \times .395}{.417}\left(\frac{1.67^2 \times 4.716 \times 10^9}{1.36 + 1.67}\right)^{.278} = 61.1 \frac{BTU}{FT^2 - HR - {}^{\circ}F}$$

$$= 61.1 \times \left(1.356 \times 10^{-4}\right) = .00829 \frac{CAL}{CM^2\text{-}SEC\text{-}{}^{o}C}$$

$$\left.\frac{hc}{\Delta T^{.278}}\right)_{225^{o}F} = \frac{.00829}{(22.2)^{.278}} = .0035 \frac{CAL}{CM^2\text{-}SEC\text{-}{}^{o}C\text{-}{}^{o}C^{.278}}$$

Since there are two walls in my model each one would have twice the heat transfer capability given above.

$$\left.\frac{hc}{\Delta T^{.278}}\right)_{225^{o}C} = .007 \frac{CAL}{CM^2\text{-}SEC\text{-}{}^{o}C\text{-}{}^{o}C^{.278}}$$

$TW \approx 15^{o}C \simeq 60^{o}F$

$$Gr = 18.4 \times 10^6 \times 40 \times .417^3 = 5.33 \times 10^7$$

$$hc = .135 \times \frac{.340}{.417}\left(\frac{8.03^2 \times 5.33 \times 10^7}{1.36 + 8.03}\right)^{.278} = 26.4 \frac{BTU}{FT^2\text{-}HR\text{-}{}^{o}F}$$

$$\left.\frac{hc}{\Delta T^{.278}}\right)_{60^{o}F} = .007 \times \frac{26.4}{61.1} = .0031 \ \frac{CAL}{CM^{2}\text{-}SEC\text{-}^{o}C\text{-}^{o}C^{.278}} \quad .$$

CONVECTION IN AIR

During the accident the shield water is lost so that convection is via air rather than water.

$T \cong 150^{o}C \approx 300^{o}C$

$\Delta T = 40^{o}F = 22.2^{o}C$

$b = 5.0$ inches $= .417$ ft

Using EQ (6.10) from Reference 2 ,

$$hc = \frac{.135\ Km}{b}\left(\frac{Pr^{2}\ Gr}{1.36 * Pr}\right)^{.278}$$

$$Gr = \frac{g\beta\rho^{2}}{\mu^{2}} \times \Delta T \times b^{3} = .444 \times 10^{6} \times 40 \times .417^{3} = 1.29 \times 10^{6}$$

$$hc = \frac{.135 \times .0193}{.417}\left(\frac{.71^{2} \times 1.29 \times 10^{6}}{1.36 + .71}\right)^{.278} = .211 \ \frac{BTU}{FT^{2}\text{-}HR\text{-}^{o}F}$$

$$hc = .211 \times \left(1.356 \times 10^{-4}\right) = 2.86 \times 10^{-5} \frac{CAL}{CM^{2}\text{-}SEC\text{-}^{o}C}$$

$$\left.\frac{hc}{\Delta T^{.278}}\right)_{150^{o}C} = \frac{2.86 \times 10^{-5}}{(22.2)^{.278}} = 1.21 \times 10^{-5} \ \frac{CAL}{CM^{2}\text{-}SEC\text{-}^{o}C\text{-}^{o}C^{.278}} \quad .$$

Note that the above heat transfer coefficient is so small that most heat transfer between the outer shell and the corrugated containment will be by radiation under this condition.

CONVECTION IN THE WATER

INNER CHAMBER (Nodes 101 → 108 to 121 → 128)

TW ≈ 150°C ≈ 300°F

$\Delta T = 10^0F = 5.56^0C$

ID of inner chamber = 37.5 inches

$$\overline{Gr} = \frac{g\ B\ \rho^2\ (\Delta T)\ L^3}{\mu^2} = 4 \times 10^9 \times 10 \times \frac{37.5}{12} = 1.22 \times 10^{12}$$

Using equation 7-22 from Kreith (Ref. 4) ,

$$\overline{NU} = .024 \times \left( \frac{Pr^{1.17}}{1+ .494\ Pr^{2/3}}\ \overline{Gr} \right)^{.4}$$

$$\overline{NU} = .024 \left( \frac{1.18^{1.17}}{1+ .494 \times 1.18^{2/3}}\ 1.22 \times 10^{12} \right)^{.4}$$

$$\overline{NU} = 1486.23$$

$$hc = \overline{NU}\ \frac{Km}{L} = \frac{1486.23 \times .395}{37.5/12} = 187.9\ \frac{BTU}{FT^2\text{-}HR\text{-}^0F}$$

$$hc = 187.9 \times \left( 1.356 \times 10^{-4} \right) = .0255\ \frac{CAL}{CM^2\text{-}SEC\text{-}^0C\text{-}^0C^{.4}}$$

$$\left. \frac{hc}{(\Delta T)^{.4}} \right)_{150^0C} = \frac{.0255}{(5.56)^{.4}} = .0128\ \frac{CAL}{CM^2\text{-}SEC\text{-}^0C\text{-}^0C^{.4}}$$

Tw ≈ 70°C ≈ 150°F

$$\overline{Gr} = .44 \times 10^9 \times 10 \times \frac{37.5}{12}^{3} = 1.34 \times 10^{11}$$

$$\overline{NU} = .024\left(\frac{2.74^{1.17}}{1+.484 \times 2.74^{.66}} 1.34 \times 10^{11}\right)^{.4} = 828.8$$

$$\left.\frac{hc}{(\Delta T)^{.4}}\right)_{70^0C} = .0128 \times \frac{828.8}{1486.23} = .0071 \frac{CAL}{CM^2\text{-}SEC\text{-}^0C\text{-}^0C^{.4}}$$

CONVECTION IN WATER

INNER CHAMBER TO FUEL RODS (Nodes 121 → 128 to 141 → 148)

Tw = 150°C ≈ 300°F

$\Delta T = 10^0F = 5.56^0C$

ROD DIAMETERS = .422 inches = .035 ft

from Kreith (Ref. 4) Eq. 7-28 ,

$$Nu = .53\ (Gr\ P_r)^{.25}$$

$$Gr = \frac{gB\rho^2}{\mu^2} = 4 \times 10^9 \times 10 \times .035^3 = 1.72 \times 10^6$$

$$Nu = .53 \times (1.72 \times 10^6 \times 1.18)^{.25} = 20$$

$$hc = Nu \times \frac{Km}{L} = \frac{20 \times .395}{.035} = 225.6 \frac{BtU}{FT^2\ HR\ \ -^0F}$$

$$hc = 225.6 \times \left(1.356 \times 10^{-4}\right) = .0306 \frac{CAL}{CM^2 - SEC - °C -}$$

$$\left.\frac{hc}{\Delta T^{.25}}\right)_{150°C} = \frac{.0306}{(5.56)^{.25}} = .020 \frac{CAL}{CM^2 - SEC - °C - °C^{.25}} \quad .$$

The ratio of the total perimeter of all the rods to the inside and outside area of the anulus representing the rods is

$$\frac{PR}{PA} = \frac{1372 \times \Pi \times .422 \times 2.54}{\pi \times 27.93 + \Pi \times 19.7} = 30.9 \quad .$$

Thus if we account for the area ratio in the heat transfer coefficient

$$\left.\frac{hc}{\Delta T^{.25}}\right)_{150°C} = .02 \times 30.9 = .62 \frac{CAL}{CM^2 - SEC - °C = °C^{.25}} \quad .$$

Cutting this value in half to account for the flow restrictions of multiple rods

$$\left.\frac{hc}{\Delta T^{.25}}\right)_{150°C} = .31 \frac{CAL}{CM^2 - SEC - °C - °C^{.25}} \quad .$$

<u>Tw≈70°C ≈ 150°F</u>

$$\overline{Gr} = .44 \times 10^9 \times 10 \times 035^3 = 1.89 \times 10^5$$

$$\overline{NU} = .53 \times (1.89 \times 10^5 \times 2.74)^{.25} = 14.2$$

$$\left.\frac{hc}{\Delta T^{.25}}\right)_{70°C} = .31 \times \frac{14.2}{20} = .22 \frac{CAL}{CM^2 - SEC - °C - °C^{.25}} \quad .$$

CASK EXTERIOR HEAT TRANSFER

HEAD OF CASK

The head of the cask is covered with a series of fins. A calculation was performed to determine if the boundary layer from one fin conflicts with that of another fin. It was found that the spacing of the fins is sufficient that no conflict should occur, consequently standard vertical plate heat transfer correlations adjusted for the angle of the fin from vertical may be used. Kreith (Ref. 4) Eq. 7-19 gives the following formula for a vertical plate.

$$hc = .48 \frac{Km}{X} (Gr)^{.25}$$

Evaluating the Equation at 100°F,

$$hc = .48 \frac{.0154}{X} (1.76 \times 10^{-6} \times \Delta T - X^3)^{.25}$$

$$= .27 \left(\frac{\Delta T}{L}\right)^{.25} \quad .$$

This formula is nearly the same as Eq. 6.3 in Reference 2,

$$hc = .29 \left(\frac{\Delta T}{L}\right)^{.25} \quad .$$

In the interest of maintaining similarity between Reference 2 and our analysis, the latter equation will be used as a bases for analyzing the cask. It, however, must be modified to account for the slant of the fins.

We will calculate separate heat transfer coefficients for the fins and the head of the cask proper since the uninterrupted path of the air flowing over the two is different.

## CASK HEAD

The formula we shall use for free convection from a non-vertical plate is

$$hc = .29 \left(\frac{\Delta T}{L}\right)^{.25} \text{Cos } \Theta^{.75} \quad .$$

The average effect of the non vertical air path will be found by averaging Cos $\Theta^{.75}$ for the 16 fins on the cask.

$$\left.\text{Cos } \Theta^{.75}\right)\text{ave} = \frac{1.0 + 1.0 + .806 * 4 + .77 \times 4 + .484 \times 4 + 0 + 0}{16}$$

$$\left.\text{Cos } \Theta^{.75}\right)\text{ave} = .641 \quad .$$

The length of the air path taken by the air cooling the head of the cask is the diameter of the cask. Thus with $\Delta T = 50°F = 27.8°C$ ,

$$hc = .29 \times \left(\frac{50}{4.14}\right)^{.25} \times .641 = .347 \frac{\text{BtU}}{\text{FT}^2 - \text{Hr} - °\text{F}}$$

$$hc = .347 \times (1.356 \times 10^{-4}) = .000047 \frac{\text{CAL}}{\text{CM}^2 - \text{SEC} - °\text{C}} \quad .$$

$$\frac{hc}{\Delta T^{.25}} = \frac{.000047}{(27.8)^{.25}} = .00002 \frac{\text{CAL}}{\text{CM}^2 - \text{SEC} - °\text{C} - °\text{C}^{.25}}$$

## CASK HEAD FINS

Calculation of the heat transfer coefficients from the fins on the head of the cask proceed in an indentical manner except the length of path the air takes is different:

FOR LONG FINS

$$\frac{hc}{\Delta T^{.25}} = .000024 \frac{CAL}{CM^2 - SEC - °C - °C^{.25}} \quad .$$

FOR COMBINATION OF LONG AND SHORT FINS

$$\frac{hc}{\Delta T^{.25}} = .000026 \frac{CAL}{CM^2 - SEC - °C - °C^{.25}} \quad .$$

Side of Cask

FORCFD CONVECTION

In lieu of any better data on the flow rate of the blowers and the configuration of the air distribution system used on the cask, the heat transfer coefficients calculated in Reference ? page 6-33, which were based on Reference 5, were used in our analysis. The value of heat transfer coefficient (7.0 BTU/FT$^2$-HR-°F) is a reasonable value for a forced air convection system.

FREE CONVECTION

Diameter of the Cask = 61.61 inches = 5.13 ft.

Assume $\Delta T$ = 100°F = 55.6°C

TEMP = 180°F

$$Gr = \frac{g\beta\rho^2}{\mu^2} x \Delta T x L^3 = 1.03 \times 10^6 \times 100 \times 5.13^3$$

$$Gr = 1.39 \times 10^{10} .$$

From reference 4, Figure (7-4),

$$hc = \frac{Km}{D} x .021 \times (Gr x Pr)^{.4} = \frac{.017}{5.13} \times .021 \times (1.39 \times 10^{10} \times .73)^{.4}$$

$$hc = .7 \frac{BtU}{FT^2 - HR - °F}$$

$$hc = .17 \times (1.356 \times 10^{-4}) = 9.49 \times 10^{-5} \ \frac{CAL}{CM^2 - SEC - °C}$$

$$\frac{hc}{\Delta T^{\cdot 4}} = \frac{9.49 \times 10^{-5}}{55.6^{\cdot 4}} = .000019 \ \frac{CAL}{CM^2 - SEC - °C \ °C^{\cdot 4}}$$

# APPENDIX B

## LISTING OF TRUMP MODEL

```
BOX 280 MEIER
TRUMP CASK PROBLEM. SOAK AT 35 C. CASKF9A
BLOCK 1    RECTAN
   000                      500   30      1                                         1.355E-12
     1      1                     1.0                       7200.
          100.

BLOCK 4  RECTANGULAR NODE CARDS
    45                 1                  129.        5.       0.9
    46                 1                  129.        5.       0.9
   236      2     1    1                  13.55      4.45      3.49
   351                 1                   3.02      20.       3.96
   356                 1                   3.02      20.      10.16
   361                 1                   3.02      20.       1.27
   366                 1                   3.02      15.      21.5
   371                 1                   3.02      10.       8.24
   381                 1                   3.02      20.      15.4
   331                 1                   5.12      20.      15.4
   281                 1                   7.62      20.      15.4

BLOCK 5 RECTANGULAR INTERNAL RESISTANCES
   281  251                   7.7       .100       .96     162.56
   331  301                   7.7       .100       .64     162.56
   351  356                   1.98      5.00      3.02     162.56
   356  361                   5.36       .63      3.02     162.56
   361  366                    .63      8.85      3.02     162.56
   366  371                   8.85      4.12      3.02      81.28
   301  351                   7.7       1.96      3.02     162.56
   281  331                   3.84      2.56     15.40      20.32
   301  351                   2.56     12.00      3.96      20.32
   306  356                   2.56     12.00     10.16      20.32
   311  361                   2.56     12.08      1.27      20.32
   316  366                   2.56     12.88      9.85      20.32
   321  371                   2.56     12.00      8.24      10.16
   331  301                   2.56     12.09     15.40      20.32
    65   45   3   1   0       1.93      8.90      30.        5.30
    45   46                   8.90      0.90     120.8       5.38
   306  236                   .001      1.69      4.45      13.97
   236  237                 1.69        1.69      4.45      13.97
   237  238                 1.69        1.69      4.45      13.97
   238  206                 1.69        .100      4.45      13.97

BLOCK 1           AXISSYMETRIC
   000                      500   30      1                                         1.355E-12
     2      1                     1.0                       7200.
          100.

BLOCK 4A  ASYMETRIC NODE CARDS
     1     3     1     1                   5.38       .38      78.72
    21     3     1     3                   5.38      7.7       74.69
    41     3     1     3                   5.38      7.70      66.91
    61     3     1     1                   5.38      3.96      61.04
    81     3     1     2                   5.38     10.16      53.98
   101     3     1     1                   5.38      1.27      48.27
   121     3     1     3                   5.38     21.5       37.79
   141     3     1     4                   5.38      8.24      23.82
   161     3     1     3                   5.38     21.5        9.85
    65     3     1     1                   1.35      3.96      61.04
    85     3     1     2                   1.35     10.16      53.98
   105     3     1     1                   1.35      1.27      48.27
```

LISTING OF TRUMP MODEL

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 61 | 125 | 3 | | 1 | 3 | | 1.35 | 21.5 | 37.78 | | |
| 62 | 145 | 3 | | 1 | 4 | | 1.35 | 8.24 | 23.82 | | |
| 63 | 165 | 3 | | 1 | 3 | | 1.35 | 21.5 | 9.85 | | |
| 64 | 201 | | | | 1 | | .32 | 3.96 | 61.04 | | |
| 65 | 206 | | | | 1 | | .32 | 10.16 | 53.98 | | |
| 66 | 211 | | | | 1 | | .32 | 1.27 | 48.27 | | |
| 67 | 216 | | | | 1 | | .32 | 21.5 | 37.78 | | |
| 68 | 221 | | | | 1 | | .32 | 8.24 | 23.82 | | |
| 69 | 226 | | | | 1 | | .32 | 21.5 | 9.85 | | |
| 70 | 251 | | | | 1 | | .96 | 3.96 | 61.04 | | |
| 71 | 256 | | | | 1 | | .96 | 10.16 | 53.98 | | |
| 72 | 261 | | | | 1 | | .96 | 1.27 | 48.27 | | |
| 73 | 266 | | | | 2 | | .96 | 21.5 | 37.78 | | |
| 74 | 271 | | | | 2 | | .96 | 8.24 | 23.82 | | |
| 75 | 276 | | | | 2 | | .96 | 21.5 | 9.85 | | |
| 76 | 301 | | | | 1 | | .64 | 3.96 | 61.04 | | |
| 77 | 306 | | | | 1 | | .64 | 10.16 | 53.98 | | |
| 78 | 311 | | | | 1 | | .64 | 1.27 | 48.27 | | |
| 79 | 316 | | | | 1 | | .64 | 21.5 | 37.78 | | |
| 80 | 321 | | | | 1 | | .64 | 8.24 | 23.82 | | |
| 81 | 326 | | | | 1 | | .64 | 21.5 | 9.85 | | |
| 82 | | | | | | | | | | | |
| 83 | BLOCK 5A AXYSIMETRIC INTERNAL RESISTANCES | | | | | | | | | | |
| 84 | 1 | 2 | 2 | 1 | 1 | 21.5 | 21.5 | .375 | 49.27 | | |
| 85 | 21 | 22 | 2 | 1 | 1 | 21.5 | 21.5 | .971 | 74.69 | | |
| 86 | 41 | 42 | 2 | 1 | 1 | 21.5 | 21.5 | .971 | 66.91 | | |
| 87 | 61 | 62 | 2 | 1 | 1 | 21.5 | 21.5 | .499 | 61.04 | | |
| [illegible] | 81 | 82 | 2 | 1 | 1 | 21.5 | 21.5 | 1.270 | 53.98 | | |
| 89 | 101 | 102 | 2 | 1 | 1 | 21.5 | 21.5 | .151 | 49.27 | | |
| 90 | 121 | 122 | 2 | 1 | 1 | 21.5 | 21.5 | 2.460 | 37.78 | | |
| 91 | 141 | 142 | 2 | 1 | 1 | 21.5 | 21.5 | 1.03 | 23.82 | | |
| 92 | 161 | 162 | 2 | 1 | 1 | 21.5 | 21.5 | 2.460 | 9.85 | | |
| 93 | 64 | 65 | 0 | 0 | 0 | 21.5 | 5.38 | .499 | 61.04 | | |
| 94 | 84 | 85 | 0 | 0 | 0 | 21.5 | 5.38 | 8.270 | 53.93 | | |
| 95 | 104 | 105 | 0 | 0 | 0 | 21.5 | 5.38 | .151 | 49.27 | | |
| 96 | 124 | 125 | 0 | 0 | 0 | 21.5 | 5.38 | 2.460 | 37.78 | | |
| 97 | 144 | 145 | 0 | 0 | 0 | 21.5 | 5.38 | 0.03 | 23.82 | | |
| 98 | 164 | 165 | 0 | 0 | 0 | 21.5 | 5.30 | 2.460 | 9.85 | | |
| 99 | 65 | 66 | 2 | 1 | 1 | 5.38 | 5.30 | .479 | 61.04 | | |
| 100 | 85 | 86 | 2 | 1 | 1 | 5.38 | 5.38 | 1.270 | 53.98 | | |
| 101 | 105 | 106 | 2 | 1 | 1 | 5.38 | 5.38 | .151 | 49.27 | | |
| 102 | 125 | 126 | 2 | 1 | 1 | 5.38 | 5.38 | 2.460 | 37.78 | | |
| 103 | 145 | 146 | 2 | 1 | 1 | 5.38 | 5.38 | 1.03 | 23.92 | | |
| 104 | 165 | 166 | 2 | 1 | 1 | 5.38 | 5.38 | 2.460 | 9.85 | | |
| 105 | 1 | 21 | 3 | 1 | 1 | .15 | .001 | 5.38 | 78.52 | .00700 | -.267 |
| 106 | 21 | 41 | 3 | 1 | 1 | .01 | .01 | 5.38 | 70.80 | | |
| 107 | 41 | 61 | 3 | 1 | 1 | .001 | 1.98 | 5.38 | 63.02 | .00700 | -.267 |
| 108 | 61 | 81 | 3 | 1 | 1 | 1.98 | 5.08 | 5.38 | 59.06 | | |
| 109 | 81 | 101 | 3 | 1 | 1 | 5.08 | .63 | 5.38 | 48.90 | | |
| 110 | 101 | 121 | 3 | 1 | 1 | .63 | .001 | 5.38 | 47.63 | .01280 | -.40 |
| 111 | 121 | 141 | 3 | 1 | 1 | .001 | .360 | 5.38 | 27.93 | .31 | -.25 |
| 112 | 141 | 161 | 3 | 1 | 1 | .360 | .001 | 5.38 | 21.5 | .31 | -.25 |
| 113 | 65 | 85 | 3 | 1 | 1 | 1.90 | 5.08 | 1.35 | 59.06 | | |
| 114 | 85 | 105 | 3 | 1 | 1 | 5.08 | .63 | 1.35 | 48.90 | | |
| 115 | 105 | 125 | 3 | 1 | 1 | .63 | .001 | 1.35 | 47.63 | .01280 | -.40 |
| 116 | 125 | 145 | 3 | 1 | 1 | .001 | .360 | 1.35 | 27.93 | .31 | -.25 |
| 117 | 145 | 165 | 3 | 1 | 1 | .360 | .001 | 1.35 | 21.5 | 31 | -.25 |
| 119 | 201 | 206 | | | | 1.98 | 5.08 | .32 | 59.06 | | |
| 119 | 206 | 211 | | | | 5.08 | .63 | .32 | 48.90 | | |
| 120 | 211 | 216 | | | | .63 | 8.85 | .32 | 47.63 | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 121 | 216 | 221 | | | | 8.85 | 4.12 | .32 | 27.93 | | |
| 122 | 221 | 226 | | | | 4.12 | 8.85 | .32 | 21.5 | | |
| 123 | 251 | 256 | | | | 1.98 | 5.08 | .96 | 59.06 | | |
| 124 | 256 | 261 | | | | 5.08 | .63 | .96 | 48.98 | | |
| 125 | 261 | 266 | | | | .63 | 8.85 | .96 | 47.63 | | |
| 126 | 266 | 271 | | | | 8.85 | 4.12 | .96 | 27.93 | | |
| 127 | 271 | 276 | | | | 4.12 | 8.85 | .96 | 21.5 | | |
| 128 | 301 | 306 | | | | 1.90 | 5.08 | .64 | 59.06 | | |
| 129 | 306 | 311 | | | | 5.08 | .63 | .64 | 48.98 | | |
| 130 | 311 | 316 | | | | .63 | 8.85 | .64 | 47.63 | | |
| 131 | 316 | 321 | | | | 8.85 | 4.12 | .64 | 27.93 | | |
| 132 | 321 | 326 | | | | 4.12 | 8.85 | .64 | 21.5 | | |
| 133 | 201 | 251 | | | | 1.28 | 3.84 | .499 | 61.04 | | |
| 134 | 206 | 256 | | | | 1.28 | 3.84 | 1.27 | 53.98 | | |
| 135 | 211 | 261 | | | | 1.28 | 3.84 | .151 | 48.27 | | |
| 136 | 216 | 266 | | | | 1.29 | 3.84 | 2.46 | 37.78 | | |
| 137 | 221 | 271 | | | | 1.28 | 3.84 | 1.03 | 23.82 | | |
| 138 | 226 | 276 | | | | 1.29 | 3.84 | 2.46 | 9.85 | | |
| 139 | 251 | 301 | | | | 3.84 | 2.56 | .499 | 61.04 | | |
| 140 | 256 | 306 | | | | 3.84 | 2.56 | 1.270 | 53.98 | | |
| 141 | 261 | 311 | | | | 3.84 | 2.56 | .151 | 48.27 | | |
| 142 | 266 | 316 | | | | 3.84 | 2.56 | 2.46 | 37.78 | | |
| 143 | 271 | 321 | | | | 3.84 | 2.56 | 1.03 | 23.81 | | |
| 144 | 276 | 326 | | | | 3.84 | 2.56 | 22.46 | 9.85 | | |
| 145 | 68 | 201 | | | | 5.38 | 1.28 | .499 | 61.04 | | |
| 146 | 88 | 206 | | | | 5.38 | 1.28 | 1.270 | 53.98 | | |
| 147 | 108 | 211 | | | | 5.38 | 1.28 | .151 | 48.27 | | |
| 148 | 128 | 216 | | | | .001 | 1.28 | 2.46 | 37.78 | .01288 | -.48 |
| 149 | 148 | 221 | | | | .001 | 1.28 | 1.03 | 23.92 | .01288 | -.40 |
| 150 | 168 | 226 | | | | .001 | 1.28 | 2.463 | 9.85 | .01280 | -.40 |
| 151 | | | | | | | | | | | |
| 152 | BLOCK 6 | ASYMETRIC BOUNDRY RESISTANCES | | | | | | | | | |
| 153 | 301 | 501 | 0 | 0 | 0 | 0 | .495 | 61.04 | .000020 | | .25 |
| 154 | 306 | 501 | | | | | 1.27 | 54.00 | .000020 | | .25 |
| 155 | 311 | 501 | | | | | .159 | 48.24 | .000020 | | .25 |
| 156 | 316 | 501 | | | | | 2.814 | 36.81 | .000020 | | .25 |
| 157 | 321 | 501 | | | | | .329 | 23.81 | .000020 | | .25 |
| 158 | 326 | 501 | | | | | 2.813 | 11.25 | .000020 | .83 | .25 |
| 159 | 331 | 501 | | | | | 40.96 | 2.54 | .000024 | | .25 |
| 160 | 351 | 501 | | | | | 193.28 | 9.71 | .000024 | | .25 |
| 161 | 356 | 501 | | | | | 193.28 | 8.59 | .000024 | | .25 |
| 162 | 361 | 501 | | | | | 193.28 | 7.68 | .000024 | | .25 |
| 163 | 366 | 501 | | | | | 193.28 | 5.86 | .000824 | | .25 |
| 164 | 371 | 501 | | | | | 96.64 | 3.79 | .000024 | | .25 |
| 165 | 381 | 501 | | | | | 193.28 | 2.54 | .000024 | | .25 |
| 166 | 351 | 501 | | | | | .347 | 61.04 | | .83 | |
| 167 | 356 | 501 | | | | | .989 | 54.00 | | .83 | |
| 168 | 361 | 501 | | | | | .159 | 48.24 | | .83 | |
| 169 | 366 | 501 | | | | | 1.970 | 36.81 | | .83 | |
| 170 | 371 | 501 | | | | | .230 | 23.81 | | .93 | |
| 171 | 301 | 501 | | | | | .149 | 61.94 | | .83 | |
| 172 | 306 | 501 | | | | | .381 | 54.00 | | .83 | |
| 173 | 316 | 501 | | | | | .6440 | 36.91 | | .93 | |
| 174 | 321 | 501 | | | | | .099 | 23.81 | | .83 | |
| 175 | 301 | 501 | | | | | 5.12 | 2.54 | | .83 | |
| 176 | 281 | 501 | | | | | 61.44 | 2.54 | .000020 | | .25 |
| 177 | 251 | 501 | | | | | .96 | 63.03 | .000019 | | .4 |
| 178 | 201 | 501 | | | | | .32 | 63.03 | .000019 | | .4 |
| 179 | 45 | 501 | | | | | 236.64 | 2.54 | .000012 | | .4 |
| 180 | 46 | 501 | | | | | 236.64 | .58 | .000012 | | .4 |

```
    4  501                         10.95      78.87        .00095
    3  501                         10.95      78.87        .00095
    2  501                         10.95      78.87        .00095
    1  501                         10.95      78.87        .00095
  301  501                          .64       63.07        .000019                          .4
   65  501     3     1     0       1.35       27.31        .000019                          .4
  301  501                         3.02       78.42                   .84
  331  501                          .45       78.42                   .84
  291  501                          .67       78.42                   .84
  301  501                          .19       78.42                   .84
  251  501                          .29       78.42                   .84
  201  501                          .32       63.02                   .84
   46  501                         3.12       79.                     .84
   45  301                         1.10       79.                     .84
   60  501                         1.00       79.                     .84
    4  501                         5.38       79.                     .84
    3  501                         5.38       79.                     .84
    2  501                         5.38       79.                     .84
    1  501                         5.38       79.                     .84

BLOCK 7  BOUNDRY NODES
  501    0                    35.0

BLOCK 2
STEEL     1                 8    3        7.84        .12
      .03142       37.8     .03514        149.      .03927        260.
URANI     2                 2    3        19.29
       .020         24.      .033        260.
      .05912       37.8     .06573        149.      .07400        260.
WATER     3                 4    4        1.00                                0.0
        1.01          0       .998        21.         1.0         93.       1.00          500.
      .00132          0     .00143        21.       .00165        93.     .00158          500.
FUEL      4                 0    0        6.9        .085        .021
WATR2     5                 4    0        1.00
        1.01          0       .998        21.         1.0         93.       1.00          204.

BLOCK11   GRAPHICAL OUTPUT
    5
    4   65   105   145   237   256   261   251    80

**     TRUMP CASK PROBLEM 130F, F          10:29:02Z 04/26/77
BLOCK 9.   T, A, B, G AT TIME                           7.64553E+03          91
   45                          35. 0.       0.        0.
   46                          35. 0.       0.        0.
  236                          35. 0.       0.        0.
  237                          35. 0.       0.        0.
  238                          35. 0.       0.        0.
  351                          35. 0.       0.        0.
  356                          35. 0.       0.        0.
  361                          35. 0.       0.        0.
  366                          35. 0.       0.        0.
  371                          35. 0.       0.        0.
  381                          35. 0.       0.        0.
  331                          35. 0.       0.        0.
  281                          35. 0.       0.        0.
    1                          35. 0.       0.        0.
    2                          35. 0.       0.        0.
    3                          35. 0.       0.        0.
    4                          35. 0.       0.        0.
   21                          35. 0.       0.        0.
```

| | | | | | |
|---|---|---|---|---|---|
| 241 | 22 | 35. | 0. | 0. | 0. |
| 242 | 23 | 35. | 0. | 0. | 0. |
| 243 | 24 | 35. | 0. | 0. | 0. |
| 244 | 41 | 35. | 0. | 0. | 0. |
| 245 | 42 | 35. | 0. | 0. | 0. |
| 246 | 43 | 35. | 0. | 0. | 0. |
| 247 | 44 | 35. | 0. | 0. | 0. |
| 248 | 61 | 35. | 0. | 0. | 0. |
| 249 | 62 | 35. | 0. | 0. | 0. |
| 250 | 63 | 35. | 0. | 0. | 0. |
| 251 | 64 | 35. | 0. | 0. | 0. |
| 252 | 81 | 35. | 0. | 0. | 0. |
| 253 | 82 | 35. | 0. | 0. | 0. |
| 254 | 83 | 35. | 0. | 0. | 0. |
| 255 | 84 | 35. | 0. | 0. | 0. |
| 256 | 101 | 35. | 0. | 0. | 0. |
| 257 | 102 | 35. | 0. | 0. | 0. |
| 258 | 103 | 35. | 0. | 0. | 0. |
| 259 | 104 | 35. | 0. | 0. | 0. |
| 260 | 121 | 35. | 0. | 0. | 0. |
| 261 | 122 | 35. | 0. | 0. | 0. |
| 262 | 123 | 35. | 0. | 0. | 0. |
| 263 | 124 | 35. | 0. | 0. | 0. |
| 264 | 141 | 40. | 0. | 0. | 3.450E-02 |
| 265 | 142 | 40. | 0. | 0. | 3.450E-02 |
| 266 | 143 | 40. | 0. | 0. | 3.450E-02 |
| 267 | 144 | 40. | 0. | 0. | 3.450E-02 |
| 268 | 161 | 35. | 0. | 0. | 0. |
| 269 | 162 | 35. | 0. | 0. | 0. |
| 270 | 163 | 35. | 0. | 0. | 0. |
| 271 | 164 | 35. | 0. | 0. | 0. |
| 272 | 65 | 35. | 0. | 0. | 0. |
| 273 | 66 | 35. | 0. | 0. | 0. |
| 274 | 67 | 35. | 0. | 0. | 0. |
| 275 | 68 | 35. | 0. | 0. | 0. |
| 276 | 85 | 35. | 0. | 0. | 0. |
| 277 | 86 | 35. | 0. | 0. | 0. |
| 278 | 87 | 35. | 0. | 0. | 0. |
| 279 | 88 | 35. | 0. | 0. | 0. |
| 280 | 105 | 35. | 0. | 0. | 0. |
| 281 | 106 | 35. | 0. | 0. | 0. |
| 282 | 107 | 35. | 0. | 0. | 0. |
| 283 | 108 | 35. | 0. | 0. | 0. |
| 284 | 125 | 35. | 0. | 0. | 0. |
| 285 | 126 | 35. | 0. | 0. | 0. |
| 286 | 127 | 35. | 0. | 0. | 0. |
| 287 | 128 | 35. | 0. | 0. | 0. |
| 288 | 145 | 35. | 0. | 0. | 3.450E-02 |
| 289 | 146 | 35. | 0. | 0. | 3.450E-02 |
| 290 | 147 | 35. | 0. | 0. | 3.450E-02 |
| 291 | 148 | 35. | 0. | 0. | 3.450E-02 |
| 292 | 165 | 35. | 0. | 0. | 0 |
| 293 | 166 | 35. | 0. | 0. | 0. |
| 294 | 167 | 35. | 0. | 0. | 0. |
| 295 | 168 | 35. | 0. | 0. | 0. |
| 296 | 201 | 35. | 0. | 0. | 0. |
| 297 | 206 | 35. | 0. | 0. | 0. |
| 298 | 211 | 35. | 0. | 0. | 0. |
| 299 | 216 | 35. | 0. | 0. | 0. |
| 300 | 221 | 35. | 0. | 0. | 0. |

```
  226                    35. 0.        0.        0.
  251                    35. 0.        0.        0.
  256                    35. 0.        0.        0.
  261                    35. 0.        0.        0.
  266                    35. 0.        0.        0.
  271                    35. 0.        0.        0.
  276                    35. 0.        0.        0.
  301                    35. 0.        0.        0.
  306                    35. 0.        0.        0.
  311                    35. 0.        0.        0.
  316                    35. 0.        0.        0.
  321                    35. 0.        0.        0.
  326                    35. 0.        0.        0.
    0
*A    ID                TRUMP                        BOX Y06**TRUMP***BOX Y06
   10:29 Z04/26 745  3/5 1    5  TRUMP/77  BOX R80   MEIER              R80

ENDED-1
SPLIT
```

# APPENDIX C

## Lead-Lined Cask Analysis

## SUMMARY AND DISCUSSION

A supplemental thermal analysis study was performed on the GE TF-300 shipping cask. Its purpose was to determine the effect of replacing the four inches of uranium in the cask walls with six inches of lead. The same thermal model described in the main report was used for this with the following exceptions.

1. The appropriate dimensions in the cask body were increased by 50%.
2. The thermal properties of lead were used instead of those for uranium.

Temperatures in the seal area did not appreciably change due to the use of lead as a liner. The effect on the side of the cask is shown in the table which compares the average temperature of the lead at the mid-point of the cask with the uranium at the same point as determined in the main report.

| Condition | Lead | Uranium |
|---|---|---|
| 54.4°C (130°F) | 135.5°C | 133.2°C |
| Fire | 236.7°C | 227.1°C |

For further discussion of the analytical methods for this analysis, please see the main report.