3. THERMAL EVALUATION

3.1 Description of Thermal Design

3.1.1 Design Features

The principal feature of the thermal design is that it is completely passive; that is, no operating hardware is needed to adequately cool the package due to the heat generated by the radioactive source. The heat generation design basis is 240 watts, which corresponds to the decay heat of approximately 15,000 curies of cobalt-60. The heat generation of 20,600 Ci of cesium-137 (the package's other authorized contents) is only 97 W, so is not controlling.

The heat generated is transferred to the surface of the shipping/transfer cask (S/TC), principally by conduction through the lead, steel, and tungsten alloy materials which, except for clearances, fill the two-foot diameter container. From the surface of the cask, the decay heat is transferred by conduction, convection, and radiation through an air space, the Wooden Protective Jacket (WPJ), another air space, and through the Steel Shell to the surroundings.

The other normal transportation heat load is that imposed by insolation. The design basis solar load on the external surface of the package, as prescribed in 10 CFR 71.71(c)(1), is greater than the decay heat generation by about a factor of 15. It is a cyclical load, 12 hours on and 12 off. The influence of the insolation heat load on the S/TC is damped by the low thermal conductivity of the Wooden Protective Jacket. In insolation tests conducted at Neutron Products, Inc. over a seven-day period, the net effect of the regulation design basis heat load was to raise the surface temperature of the S/TC a maximum of 27°F at the equilibrium condition. After the third day, the surface temperature variation of the S/TC remained within a band of 3°F, even though the heating lamps remained on the 12 hours on and off cycle, and the overpack Steel Shell temperature cycled over a range of about 30°F. This shows that the thermal behavior of the S/TC and the overpack are not tightly coupled. As a result, the thermal behavior of the S/TC and the overpack can be treated independently and then combined in a simple manner to assess the thermal behavior of the total package.

Using the results of the insolation tests and a simplified thermal model for the S/TC, the maximum surface temperature of the S/TC was calculated to be 265°F for a 240 watt source under normal transport conditions. The corresponding maximum source capsule surface temperature is estimated at less than 550°F.

3.1.2 Content's Decay Heat

As discussed above, the authorized contents are 15,000 Ci of cobalt-60, which has an associated heat of decay of 240 W, and 20,600 Ci of cesium-137, with a corresponding decay heat of 97 W. The packages are shipped containing either cobalt-60 or cesium-137. Packages containing both isotopes are not authorized for shipment.

3.1.3 Summary Tables of Temperatures

Maximum package component temperatures used to evaluate thermal stresses under normal transport conditions are listed in Table 3.1.1.

The principal package protection under accidental fire conditions is provided by the overpack Wooden Protective Jacket. The jacket design is based on criteria established, in large part, on the Sandia test program results cited previously in connection with the drop tests.

Internal temperatures of the S/TC under hypothetical accident fire conditions were calculated. Using nominal values for the input parameter, the maximum overpack backface temperature (the protective jacket inner cavity surface) was 370°F. This, in turn, resulted in S/TC maximum component temperatures 125°F greater than those listed in Table 3.1.1. Maximum package component temperatures under hypothetical accident fire conditions are listed in Table 3.1.2.

These accident temperature conditions do not result in structural loadings that are significantly different from those imposed under maximum normal transport conditions. Lead melting would not occur. Reasonable differences from nominal for the value of input variables do not alter these conclusions.

TABLE 3.1.1

MAXIMUM PACKAGE TEMPERATURES
UNDER NORMAL TRANSPORT CONDITIONS [1]

Outside Steel Shell Surface	135°F	(57°C)
Outside Wooden Protective Jacket Surface	130°F	(54°C)
Inside Wooden Protective Jacket Surface	250°F	(121°C)
S/TC Surface	265°F	(129°C)
S/TC Shell Liner and Drum O.D. (Local Max.)	330°F	(165°C)
S/TC Drum Liner (Local Max.)	425°F	(218°C)
Source Capsule Surface	550°F	(288°C)

[1]240 watts corresponding to 15,000 curies of cobalt-60, and the insolation heat load prescribed in 71.71(c)(1) normalized to a reference ambient temperature of 100°F (38°C).

TABLE 3.1.2

MAXIMUM PACKAGE TEMPERATURES UNDER HYPOTHETICAL

ACCIDENT CONDITIONS[1]

Inside W P J Surface	370°F	(188°C)
S/TC Surface	385°F	(196°C)
S/TC Shell Liner and Drum O.D. (Local Max)	450°F	(232°C)
S/TC Drum Liner (Local Max)	545°F	(285°C)
Source Capsule Surface	670°F	(355°C)

[1] 240 watt source corresponding to 15,000 curies of cobalt-60 and a 1,475°F one half hour duration thermally radiative fire.

3.1.4 Summary Tables of Maximum Pressures

No pressure would build up in either the WPJ or the Steel Shell, as they are not gasketed. Even in the hypothetical accident scenario at maximum activity loading for the package, the internal pressure in the cask would not exceed 16.6 psig, as described in 3.4.3.

3.2 Material Properties and Component Specifications

3.2.1 Material Properties

The thermophysical properties of all of the materials used in the thermal evaluation are listed in Table 3.2. Also provided are the temperature range of application and source references.

TABLE 3.2

THERMAL PROPERTIES OF MATERIALS USED IN EVALUATION

Material/Property	Value	Temp. °F Range	Reference (Page)
Ferritic Steels			
Density, lbs./in.^{3}	0.284	RT-600	1.(312)
Thermal Conductivity, B/hr. ft. °F	25	RT-600	2. (83)
Specific Heat, B/lb. °F	0.125	RT-600	2.(313)
Austenitic Steels			
Density, lbs./in.^{3}	0.288	RT-600	1.(312)
Thermal Conductivity, B/hr. ft. °F	9.5	RT-300	2. (88)
	10.5	RT-450	
Specific Heat, B/lb. °F	0.125	RT-600	1.(313)
Lead			
Density, lbs./in.^{3}	0.41	RT	1.(960)
Thermal Conductivity, B/hr. ft. °F	19	RT-600	23 (380)
Specific Heat, B/lb. °F	0.032	100-500	1.(399)
Plywood			
Density, lbs./in.^{3}	36	RT-400	6.
Thermal Conductivity, B/hr. ft. °F	.085	RT	5.
Specific Heat, B/lb. °F	0.65	RT-200	4.(300)

References for Table 3.2

1. Metals Handbook, American Society for Metals (1948)

2. Boiler and Pressure Vessel Code, American Society of Mechanical Engineers, Sec. III, Div. 1, Appendices (1983)

3. W. H. McAdams, Heat Transmission, Second Edition (1942)

4. L. S. Marks, Mechanical Engineer Handbook, Fourth Edition (1941)

5. Applications Summary, American Plywood Association (1981)

6. Measured (as plywood composite)

3.2.2 Technical Specification of Components

The principal package specifications are material specifications which are listed along with the mechanical properties in Section 2.3 and the thermal properties in Section 3.2. There are no valves, or any other active components utilized in the package construction.

3.3 Thermal Evaluation under Normal Conditions of Transport

Evaluation of the package behavior under the extremes of normal transport is based on results from testing of a functional transportation package. Tests were conducted under four different internal heat loads while concurrent exterior insolation heat loads meeting or exceeding those prescribed in 10 CFR 71.71(c)(1) were imposed. The packages tested were instrumented with specially installed thermocouples. Detailed information for evaluation was obtained directly from test measurements or calculated using test calibrated simple analytical models. The package was evaluated for all of the thermal conditions identified in 10 CFR 71.71.

3.3.1 Heat and Cold

3.3.1.1 Analytical Model. For most of the thermal evaluation an analytical model comprised of concentric, spherical shells was used. Representative thermal and physical properties were determined for each shell. Internal heating was taken as being uniformly generated in an innermost ball and the heat was postulated to flow radially outward through successive shells. For external thermal input such as insolation or, in the case of accident conditions, fire loads, heat flow was postulated radially inward. For such a one-dimensional representation, the concentric sphere model best suited the source as well as the package geometry. Both overpack components are cylinders in which the height is comparable in dimension to the diameter.

Thermophysical properties were considered uniform within each shell and were established based on a weighted mass or volume basis. Where necessary, adjustments to physical constants were made based on measurements from the package insolation tests. The adjustments in thermal conductance, for example, permitted compensation for gaps and contact resistance without inordinately complicating the model.

The model and underlying assumptions, including determination of principal parameters, are described in Appendix 3.5.1.

3.3.1.2 Test Model. Tests were conducted using a functional transportation package which was instrumented with thermocouples to obtain S/TC and overpack temperatures under standard insolation conditions. Internal, as well as surface, temperatures were measured for the S/TC and overpack. The test geometry was identical to the application package.

A total of four tests were run. In two of the tests, the internal heat generation was simulated by electrical resistance heaters of 110 watts and 235 watts corresponding to 7,000 curies and 15,000 curies, respectively. In the remaining two tests, cobalt-60 was employed. The source strengths were 6,750 curies (107 watts) and 9,250 curies (146 watts). For all tests insolation heating was provided by infrared heat lamps totaling 4.5 kW input.

A summary of the test results is provided in Appendix 3.5.2, along with diagram showing the location of the temperature measurements.

3.3.1.3 Maximum Temperatures. The maximum temperatures of principal package components under normal transport conditions are provided in Table 3.1.1. These include the regulatory insolation load as defined in 10 CFR 71.71(c)(1). At an ambient temperature of 100°F, the maximum component temperatures listed would each be approximately 30°F lower in the absence of the insolation thermal load.

The maximum gasket temperature is below 300°F and the maximum lead temperature is 425°F. The gasketing material can withstand service temperatures up to 550°F and the maximum lead temperature is well below the lead melting point of 621°F. The temperature considerations and calculations are show in Appendix 3.5.3.

The maximum source capsule temperature of 550°F is well below any weld sensitization temperature for the austenitic steel encapsulating material.

3.3.1.4 Minimum Temperatures. The minimum design basis temperatures could occur only with an empty container, which is an infrequent mode of transport. Nevertheless, all of the package materials are suitable for use at the specification ambient temperature of -40°F.

When loaded with a source and otherwise being used within the design basis ambient conditions, no minimum heat load is required for safe transport of the package. A fully loaded (240 watts) package at an ambient temperature of -40°F in still air and shade would not experience significantly different component temperature differences and, hence, thermal stresses than those associated with the high limit ambient temperature. No limiting safety condition is seen at the fully loaded, low temperature operating condition.

3.3.1.5 Maximum Thermal Stresses. The only potentially significant thermal loading impacting the structural integrity of the S/TC under normal transport conditions results from the differential heating of the shell liner and the drum liner. The considerations and calculations are given in Appendix 3.5.5 for temperature and in Appendix 2.10.2 for the stresses. The stress levels are modest.

For the shell, the highest average temperature difference between the shell and internal cylindrical liner is calculated to be 15°F, which results in an axial compressive stress in the liner of less than 3,000 psi. The minimum yield strength is 31,200 psi for the material. The minimum working margin exceeds ten in compression and six in shear. This is a very low cycle displacement stress, so that there is no problem of fatigue failure.

In the case of the stainless-steel drum liner, the highest average temperature difference between the source chamber liner and the remainder of the drum structure is 33°F, which results in an axial compressive stress in the liner of less than 6,000 psi compared with a minimum yield strength of 22,500 psi for the type 304 stainless steel. The minimum working margin is 3.9 in compression and 2.3 in shear. Again, this is a very low cycle displacement stress.

3.3.2 Maximum Normal Operating Pressure

The cask is loaded dry so that the only anticipated pressure loading results from heating of the air within the enclosed cavity. In loading sources, the container internals heat up in the interval, normally less than one hour, after the source is loaded and before the closure is made. The air in the gaps heats up along with the metal components, thereby reducing subsequent pressure build up when the container is closed. However, even assuming room temperature air were sealed in the cavity void space and that it was subsequently all heated to the maximum source surface temperature (550°F), the pressure buildup would be only 13.3 psi. A more plausible maximum pressure buildup would be about half this value, or 7 psig for an internal air temperature in equilibrium with its surrounding metal. Even this is a postulated temperature limit rather than one likely to be encountered. In either case, the stress levels developed are not significant in evaluating the integrity of the components. See Appendix 3.5.4.

3.3.3 Evaluation of Package Performance for Normal Conditions of Transport

The package will satisfactorily serve its intended function under the normal transport conditions identified in 10 CFR Part 71 and will continue to do so even if many of the limiting conditions should be exceeded. The package performance is not sensitive to thermally imposed loads. For example, the maximum temperature of the lead in the S/TC would not exceed 600°F, even if the thermal rating of the source were exceeded by 50%.

In still air and shade, under an ambient temperature of 100°F, the accessible surface temperature of the package would not exceed approximately 105°F when carrying a 15,000 curie cobalt-60 source (240 watts) representative of the maximum package rating. The allowable limit in a nonexclusive use shipment is 122°F (10 CFR 71.43(g)).

Anticipated thermal and pressure loads result in stresses well below any structural limitations on the package. The principal results of the thermal evaluation are summarized in Table 3.1.1 and have been used in the Chapter 2 structural evaluation.

At the maximum 240 watt source rating under the most adverse normal transport conditions, the S/TC gasket temperature would not exceed 280°F and the source capsule surface temperature would be less than 550°F. For typical normal transport conditions both of these temperatures would be about 100°F lower, even at maximum thermal rating.

3.4 Thermal Evaluation under Hypothetical Accident Conditions

3.4.1 Initial Conditions

Under the hypothetical accident conditions, specifically the standard fire, package adequacy was demonstrated in the fire tests conducted by the Sandia Corporation in the early and middle 1960's. This work is summarized in the article by J. A. Sisler referred to previously in connection with the drop test[1]. A total of 18 wooden wall overpack containers were subjected to one hour open pit petroleum (JP-4) fires in a series of five tests, including one of the six inch minimum wall thickness

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[1] The report, "New Developments in Accident Resistant Containers for Radioactive Materials" from the Proceedings of the International Symposium for Packaging and Transportation of Radioactive Materials, January 12-15, 1965, SC-RR-65-98, Pages 141-185, has been included in Appendix 2. Both drop and fire tests are summarized.

overpacks (similar to the WPJ used in the 9215 package) which had previously been subjected to the 30 foot drop test. Tests were also conducted in the reverse order, with the fire test preceding the 30 foot drop test.

Based on the drop analysis, no significant effect on the thermal properties of the package is expected. While the overpack outer Steel Shell would be bent and crushed as a result of the free drop and possibly the puncture test, and the outer portion of the Wooden Protective Jacket that took the principal impact would be shredded, the integrity of the unit as an effective fire seal would not be affected, based on the Sandia test results. In the Sandia tests it was also shown that a small amount of plywood delamination does not have an adverse influence on the internal temperature nor the effectiveness of the overpack.

The most adverse case was considered to be a fully loaded cask, at maximum temperature, normal transport, initial conditions subjected sequentially to the drop and fire tests, in either order. The conditions in Table 3.1.1 were postulated as the starting point for the hypothetical accident.

3.4.2 Fire Test Conditions

The fires were characterized as 1,850°F black body temperature equivalents. This represents a more severe condition in both time and temperature than that specified in 10 CFR 71.73(c)(4), which calls for a ½ hour 1,475°F fire. The test results bearing on the present application were as follows:

1. Seven of the packages passed the fire tests unconditionally, six were considered conditionally satisfactory, and five failed the fire test (none of which were similar to the WPJ used in the USA/9215/B(U)).

2. All containers with six-inch thick walls passed the fire test unconditionally. (Six inches is the minimum Wooden Protective Jacket wall thickness of the present NPI package).

3. Two 4,000 pound packages were tested. Both passed the fire test unconditionally. The minimum unburned wood insulation thickness was 3-1/2 inches for one package and 4 inches for the other. Neither package employed a Steel Shell.

4. Maximum internal cavity temperatures were 160°F, or less, for both 4,000 pound packages. Based on the appearances of the internal cavity, it was believed that maximum internal temperatures for all packages with 6 inch thick walls were below 150°F, although this could not be proven because of thermocouple failure. An upper limit to the internal temperature was considered to be 300°F. Ambient temperature was not reported, but could not have had much influence because the results of tests conducted in August were similar to those conducted in January.

Pertinent conclusions concerning the proper design and construction of the Wooden Protective Jacket and its behavior under the fire test conditions are as follows:

1. Overall, Douglas Fir plywood is the favored wooden construction material for fire resistance.

2. Laminated Douglas Fir plywood walls, six inches thick, are more than adequate to prevent damaging heat transfer from the fire from reaching the inner container.

3. In the absence of heat generation by radiation sources in the inner container, the overpack cavity will experience only a modest temperature rise, typically 25°F, through the course of the fire for an adequately closed overpack.

4. A small amount of plywood delamination does not have an adverse effect on the internal temperature or the effectiveness of the overpack.

5. In the absence of internal heat generation, the temperature within the overpack cavity is likely to peak at less than 150°F and probably not exceed 300°F.

Results of these tests provide the basis for design of a satisfactory fire protection jacket for the inner lead shielded container of a shipping package. The NPI package under review more than meets the minimum requirements of overpack thickness and arrangement taught by these experiments. In addition, the NPI overpack includes an enclosing Steel Shell not employed in these experiments, which will further lag the package.

Results of the test program above notwithstanding, calculations using realistic, although simplified models, were made to provide an indication of the internal temperatures that might be expected in the course of the hypothetical accident as represented by the standard 1,475°F, one half hour fire. The calculations, along with the underlying assumptions, models, and input parameters, are provided in Appendix 3.5. The principal results of the calculations are the following:

1. At its maximum thermal rating of 240 watts (corresponding to a content of approximately 15,000 curies of cobalt-60), the adiabatic heating rate of the S/TC is 5.4°F/hr. At this heating rate and no external cooling, it would take 36 hours, starting from the maximum normal transport conditions identified in Table 3.1.1, before any cask lead would reach the 621°F melting temperature.

2. Using the post fire adiabatic equilibrium temperature of the Wooden Protective Jacket following the standard 1,475°F, one half hour fire as an upper limit to the backface temperature, the maximum overpack inner surface (backface) temperature would be 370°F.

3. Postulating the internal heating rate and maximum backface temperature given above, the maximum S/TC inner temperatures in the course of the hypothetical accident fire were calculated to be 120°F higher than the maximum values for normal transport listed in Table 3.1.1. This does not result in exceeding any limiting condition for either S/TC or source capsule. For example, the maximum temperature of the lead in the S/TC (local) remains more than 70°F below the melting temperature of 621°F during the course of the accident.

Taken together with the results of the several test programs, these calculated results show that the hypothetical accident does not produce conditions which will cause melting of the lead shielding, compromise radioactive containment, nor significantly change the radiation protective configuration of the package.

3.4.3 Maximum Temperatures and Pressure

3.4.3.1 Analytical Model. The analytical model used for evaluation of the S/TC under hypothetical accident conditions was the same as that used for normal transport assessments. The range of application permitted substantially the same input parameters to be used. The overpack prevents excessively high temperatures under the standard fire conditions.

For quantitative evaluation of the overpack under the fire condition, calculations based on the Integral Method[1] were used. In the cited work, approximate solutions to the thermal conduction (Fourier) equations were presented for several common geometries and boundary conditions utilizing the heat penetration depth concept. The spherical representations were used in the evaluation. The almost square configuration of the overpack Wooden Protective Jacket (44" OD x 45" H) best suited spherical geometry simulation. This selection was also indicated from comparison of measured with calculated temperatures in the normal transport evaluation.

The relationships used are detailed in Appendix 3.5.6. The post-fire adiabatic equilibrium temperature was used as the upper limit of the overpack (WPJ) backface temperature. The temperature drop through the outer Steel Shell was not included in the calculation. The adiabatic temperature rise rate of the S/TC was calculated from weighted specific heats of the constituent materials and the maximum rated internal heat generation rate.

3.4.3.2 Test Model. No physical models specific to this application were tested under hypothetical accident conditions. The experimental behavior of Wooden Protective Jackets under fire conditions was well established in the Sandia tests. The pertinent findings are summarized in Section 3.4 and the report is included in Appendix 2.10.9. Most of the Sandia fire tests were done using only the Wooden Protective Jackets as the overpack. In the present fire evaluation, no credit was taken for the Steel Shell surrounding the wooden jacket, which would further lag the packaging.

3.4.3.3 Package Temperature. The evaluation of peak temperature and temperature differences is simplified by taking advantage of the slow response of the Wooden Protective Jacket to imposed changes in temperature, i.e., the fire conditions. The intense heating of the fire is over before the temperature of the backface of the overpack starts to rise significantly. The backface temperature rises to a peak and then decreases. The timing of the peak is not important, but the magnitude is. The magnitude is less than the adiabatic equilibrium temperatures of the overpack calculated from the time that heating ceases. In the present instance, the peak backface temperature was taken as equal to the adiabatic equilibrium temperature and was calculated to be 370°F for the one-half hour, 1,475°F fire. The calculation is detailed in Appendix 3.5.6.

While the overpack backface is rising in temperature, the S/TC is also heating up. The adiabatic heating rate of the S/TC is 5.4°F/hr. at the maximum cask rating of 240 watts. The peak S/TC surface temperature will not exceed the overpack peak backface temperature plus the temperature drop needed to transfer the 240 watt heating load to the overpack under equilibrium steady state

[1] William H. Lake, "Thermal Analysis of Packaging Using the Integral Method," Proceedings of the Seventh International Symposium on Packaging and Transportation of Radioactive Materials, New Orleans, 1983 (PATRAM 83)

condition, in this case 370°F + 15°F = 385°F. The S/TC internal temperature distribution does not vary significantly from that for the corresponding heating load under normal transport conditions.

The envelope of limiting conditions can be assigned as the peak temperature under the HAC for evaluation of the package. The temperatures are listed in Table 3.4.1.

<u>TABLE 3.4.1</u>

MAXIMUM PACKAGE TEMPERATURES UNDER HYPOTHETICAL

ACCIDENT CONDITIONS[1]

Inside W P J Surface	370°F	(188°C)
S/TC Surface	385°F	(196°C)
S/TC Shell Liner and Drum O.D. (Local Max)	450°F	(232°C)
S/TC Drum Liner (Local Max)	545°F	(285°C)
Source Capsule Surface	670°F	(355°C)

[1] 240 watt source corresponding to 15,000 curies of cobalt-60 and a 1,475°F one half hour duration thermally radiative fire.

3.4.4 Maximum Internal Pressure

The maximum pressure developed under the hypothetical accident conditions (HAC) are only slightly higher than those reported in 3.3.2 for the normal transport case. The rationale and calculations are the same as that given in Appendix 3.5.4. For the two cases postulated, the HAC results in pressure of 16.6 psig and 10 psig, which would develop stress levels of 365 psi and 220 psi, respectively. As in the normal transport case, these stress levels are not significant in evaluating the integrity of the components.

3.4.5 Maximum Thermal Stresses

The potential temperature excursions of the S/TC components under hypothetical accident conditions result in temperature differences that fall within the bounds of those evaluated in connection with the maximum normal transport conditions. While the temperature levels are higher, the temperature differences which generate the loads are not exceeded under the accident conditions, because external heat addition tends toward lowering the temperature difference. The maximum thermal load remains on the shell and drum liners and the results of the analyses discussed in Section 3.3.1 apply to the accident conditions.

3.4.6 Evaluation of Package Performance for the Hypothetical Accident Thermal Conditions

The outermost sacrificial element of the packaging is the Steel Shell. Although it would offer some level of protection in all of the accident scenarios, no credit is taken for its protective contribution in the thermal analysis. The secondary sacrificial element of the packaging under accident conditions is the Wooden Protective Jacket. Tests, analyses, and evaluations indicate that it will maintain integrity to the extent that it will protect the S/TC from an excessive temperature rise under the sequential drop and fire exposure of the prescribed hypothetical accident. Calculations show that the temperature rise of the S/TC would be about 120°F as a result of package exposure to the fire. The Sandia tests support this range of temperature rise for a package with this configuration. This temperature rise does not threaten the integrity of the S/TC and source capsules with regard to both shielding and containment of radioactive material.

The pertinent quantitative information is summarized in Table 3.4.1 and used in Chapter 2 evaluations.

3.5 APPENDIX

3.5.1 Analytical Model

A. Calculations of Temperature Distribution

B. Determination of Principal Model Parameters

3.5.2 Summary of Insolation Tests

3.5.3 Peak Temperature Condition for Normal Transport

A. Initial Conditions

B. S/TC – Inner Container

C. Overpack

D. Summary – Values for Table 3.1.1

3.5.4 Maximum S/TC Internal Pressure

3.5.5 Maximum Thermal Stress Temperatures

A. Drum Sleeve Average

B. Drum Shell (O.D.) Average

C. Shell Liner Average

D. Summary

3.5.6 Hypothetical Accident – Fire Tests

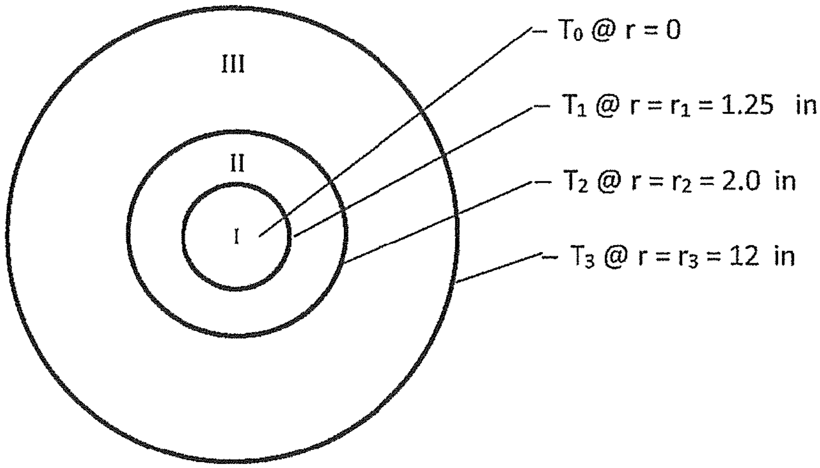
A. Adiabatic Temperature Rise of S/TC

B. Maximum Overpack Backface Temperature

C. Peak S/TC Temperature

3.5.1 Analytical Model

A. Calculation of Temperature Distribution



- The model for calculation is three concentric spheres in a steady state

- Each region has different characteristics which are determined by back calculation from the results of the insolation experiments.

- Each region is postulated to have uniform thermal characteristics, i.e., thermal conductivity, K, specific heat, Cp, and density.

- The physical boundaries of each region are as given above, except for evaluation of electrical heating tests where r_1 = 0.625" and r_2 = 4.25".

- No compensation was made for eccentricity of the source and outer shell. However, an attempt was made to match region boundaries to actual distances between source center and thermocouples. A 12-inch radius was used for the outer shell.

Region I This is the region in which most of the heat is deposited and roughly corresponds in diameter to that of the drum sleeve. In the model it is postulated that all of the heat released is generated with a uniform volumetric heat generation equal to the total heat release divided by the volume of the region. Temperature difference across the region radially:

$T_0 - T_1 = Wr_1^2 / 6K$

W = Heat generated/unit volume, BTU/ft^3

K = Thermal conductivity, Btu/hr ft °F

The temperature distribution:

$T - T_1 = (W/6K)(r_1^2 - r^2) \quad T_0 \geq T(r) \geq T_1$

Region II In this region all of the heat passes through the shell from the inside boundary. The outer boundary is approximately the distance from the source center to the drum surface to shell liner interface. The temperature difference across the region:

$$T_1 - T_2 = (q/4\pi K)\ (1/r_1 - 1/r_2)$$

q = Total heat passing through the boundary, Btu/hr.
K = Thermal conductivity

The temperature distribution:

$$T - T_2 = (q/r\pi K)\ (1/r - 1/r_2) \quad T_1 \geq T(r) \geq T_2$$

Region III Heat flow behaves as in Region II; it is postulated that all of the heat passes through the shell.

The temperature difference radially:

$$T - T_3 = (q/4\pi K)\ (1/r_2 - 1/r_3)$$

q = Total heat passing through the boundary, Btu/hr
K = Thermal conductivity

The temperature distribution:

$$T - T_3 = (q/4\ K)\ (1/r - 1/r_3) \quad T_2 \geq T_{(r)} \geq T_3$$

B. Determination of Principal Model Parameters

1. Where possible, the physical size of each region was selected based on the location of thermocouples in the insolation tests for simplicity of determining the effective thermal conductance (effective thermal conductivity), or approximately corresponding to physical regions of the S/TC. The boundary radii selected were those identified in the figure of the last section, namely:

Region I $0 \leq r \leq r_1 = 1.25$ in (0.625 in for elec. heaters)
Region II $r_1 \leq r \leq r_2 = 2.0$ in (4.25 in for elec. heaters)
Region III $r_2 \leq r \leq r_3 = 12$ in

No attempt was made to improve test data fit by changing region boundaries.

2. Based only on the materials of construction, the conductances expected would fall in the range of the conductivities for the materials, as shown in Table 3.2. However, the air gaps and contact resistances result in much lower values. Therefore, representative values were developed from temperature distribution data obtained during insolation testing reported in

3.5.2, following. Rounded values were selected based on matching the experimental data and are as follows:

Region I	$K_e = 2.5$ Btu/hr ft °F
Region II	$K_e = 2.5$ Btu/hr ft °F
Region III	$K_e = 5.0$ Btu/hr ft °F

The comparison of experimental measurements with the calculations, using the above values of conductance and region boundaries, are presented in Table 3.5.1.1. The heating rates used in the evaluation are listed in Table 3.5.1.2.

TABLE 3.5.1.1

COMPARISON OF MEASURED AND CALCULATED INNER CONTAINER (S/TC) TEMPERATURE DIFFERENCES

Temperature on Temperature Difference, °F

Test Series		T_0	ΔT_I	T_1	ΔT_{II}	T_2	ΔT_{III}	T_3	Conditions
Test A	Radius, in.	0		0.625		4.25		12	7,000 curies
T Measured, °F				411		207		190	110 watts
Δ T Measured, °F					204		17		Electric
Δ T Calculated, °F					195		11		Heating
Test B	Radius, in.	0		0.625		4.25		12	15,000 curies
T Measured, °F				711		290		251	251 watts
Δ T Measured, °F					421		39		Electric
Δ T Calculated, °F					417		24		Heating
Test C	Radius, in.	0		1.25		2.00		12	6,750 curies
T Measured, °F				253		216		190	107 watts
Δ T Measured, °F					37		26		Cobalt-60
Δ T Calculated, °F			55		41		29		Heating
T Calculated[1], °F		315		260		219		190	
Test D	Radius, in.	0		1.25		2.00		12	9,250 curies
T Measured, °F				267		206		191	146 watts
Δ T Measured, °F					61		15		Cobalt-60
Δ T Calculated, °F			>76		57		40		Heating
T Calculated[1], °F		364		288		231		191	

[1] Normalized, T_3 Measured = T_3 Calculated

TABLE 3.5.1.2

HEATING RATES USED IN INSOLATION TEST
EVALUATION CALCULATIONS

	Curies or Equivalent	Heating Watts	q Btu/hr.	W_1 Btu/hr. ft.^{3}
Test A	7,000[(1)]	110	376	NA
Test B	15,000[(1)]	235	802	NA
Test C	6,770	107	365	77,000[(2)]
Test D	9,250	146	499	106,000[(2)]

[1]Simulated by electric heaters, 63.3 Ci/watt equivalent

[2] Uniform heat generation over Region I: $r_1 = 1.25''$, vol = 0.00473 ft.^{3}

3.5.2 Summary of Insolation Tests

A series of four package insolation tests were conducted by Neutron Products in the spring and summer of 1977. In two of these tests, the internal heating was simulated by electric resistance heaters. In the other two tests, cobalt-60 sources were used.

All of the tests were done with an operational package, Model NPI 20WC-6, meeting requirements of Certificate of Compliance USA/9102/B(U). It was a lead shielded shipping/transfer cask with a 20WC-6 overpack and was essentially identical in configuration to the application package. Insolation heating was provided by incandescent lamps totaling 4.5 kilowatts which were cycled 12 hours on and 12 hours off. A test series typically lasted 7 to 9 days, during which a cyclical thermal equilibrium was established. The tests met the insolation heating requirements of what is presently prescribed under 10 CFR 71.71(c)(1).

The test results are summarized in Table 3.5.2.1. Tests A and B employed electric heaters of 110 watts and 235 watts, respectively, to simulate source heating. The heaters were placed in the position normally occupied by a source capsule in the center of one of the drum sleeves with shield plugs on both sides. In Tests C and D the drum was loaded with cobalt-60 sources as in actual transport. In Test C, two sources were used, totaling 6,750 curies (107 watts). In Test D, two sources totaling 9,250 curies (146 watts) were used. The temperatures listed in the table are keyed to the diagram in Figure 3.5.2.1, which shows the location of the thermocouples.

The temperatures listed in Table 3.5.2.1 have all been normalized to an ambient temperature of 100°F by adding the difference between 100°F and the test ambient temperature to all values, so that comparison can be made between tests. Any bias from normalization is likely to result in temperatures slightly high, but in any case, is small.

A radial temperature plot of the test results is provided in Figure 3.5.2.2.

The Test D results (not normalized) have been previously reported in the NPI August 1977 submittal, under Docket No. 71-9102.

TABLE 3.5.2.1

SUMMARY OF NPI INSOLATION TEST RESULTS

	Local Package Temperatures, °F			
Test Series	A	B	C	D
Heating Source	Electric Heaters		Cobalt-60 Sources	
Heating Power, Watts	110	235	107	146
T.C. Location/curie	-	-	6,750	9,250
1, Source chamber or heater	441	711	253	267
2. Source chamber	-	-	245	200
3. Plug chamber	207	290	216	206
4. S/TC outside – top	190	251	191	193
5. S/TC outside – side	190	250	190	192
6. S/TC outside – bottom	190	253	184	185
7. WPJ inside – bottom	181	250	190	185
8. WPJ inside – side	176	224	175	171
9. WPJ inside – top	183	236	181	186
10. WPJ outside – bottom	106	124	119	110
11. WPJ outside – side	113	141	129	131
12. WPJ outside – top	126	126	-	143
13. Steel shell outside – side	102	114	110	131
14. Ambient (normalized)	100	100	100	100

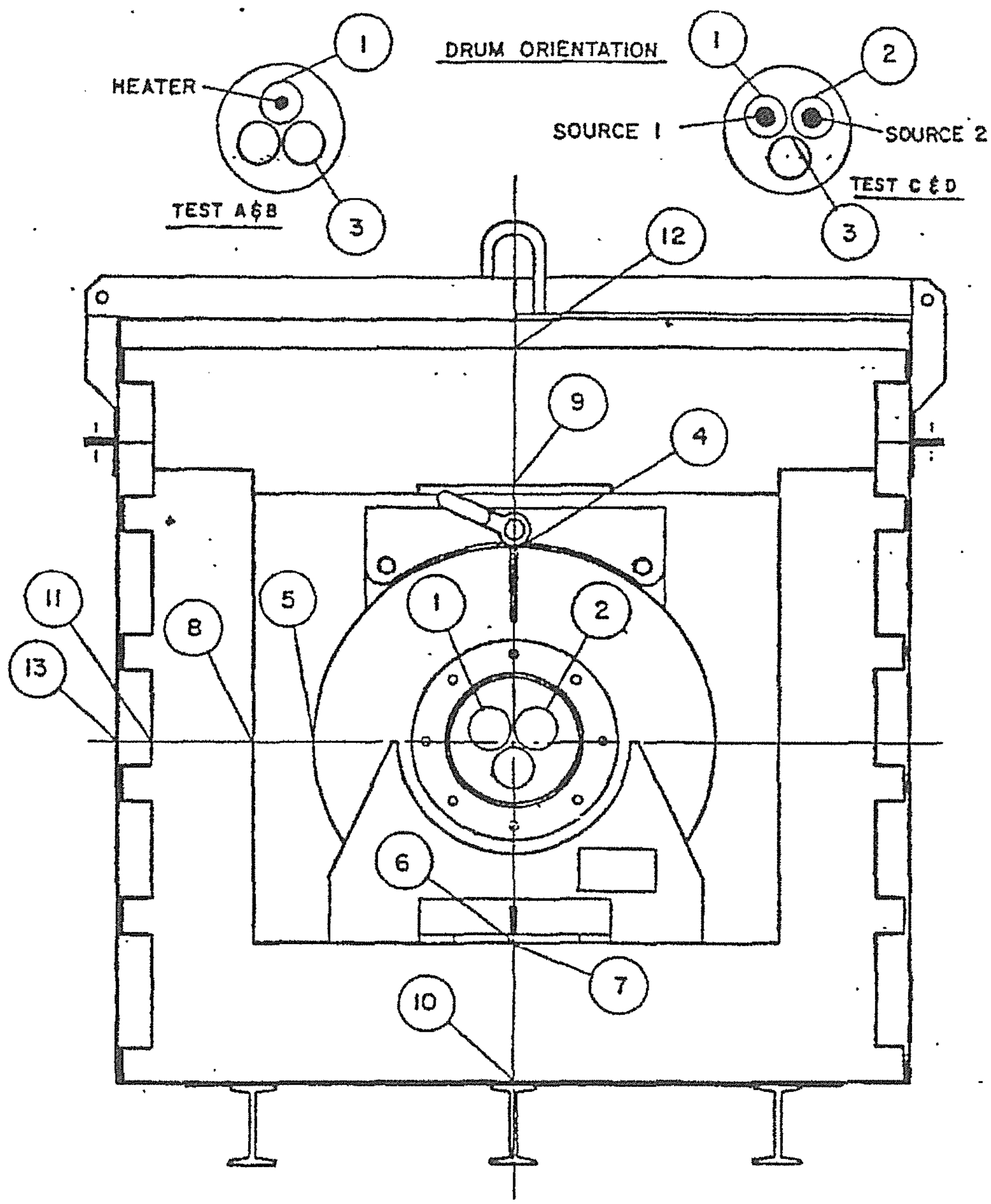


FIGURE 3.6.2.1

LOCATION OF THERMOCOUPLES IN INSOLATION TEST

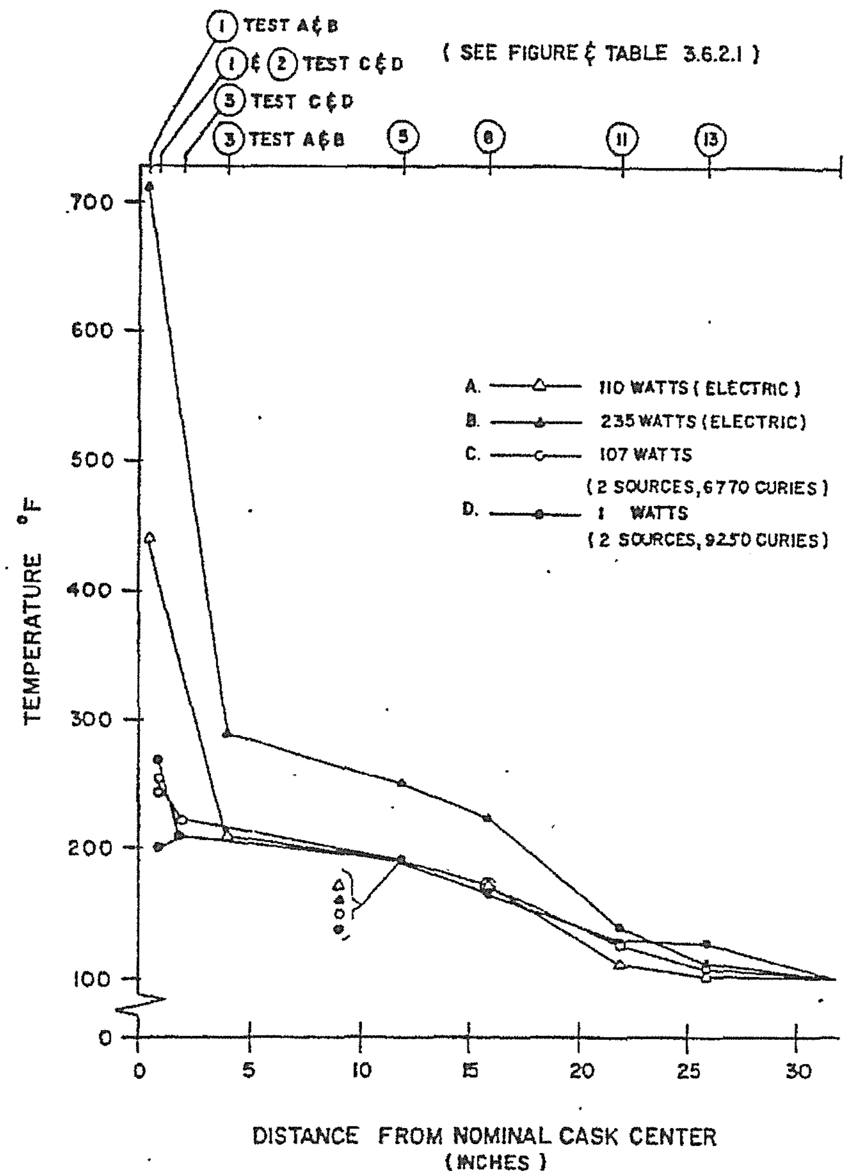


FIGURE 3.6.2.2

INSOLATION TEST RADIAL TEMPERATURE PROFILE

3-24

3.5.3 Calculation of Peak Temperature Conditions for Normal Transport

A. Initial Condition

1. S/TC with single 15,000 curie (240 watt) source
2. Ambient air, 100°F
3. Using Test B results for the overpack, the surface temperature of the S/TC for 235 watts was 250 to 253°F. this yields a ΔT from ambient to S/TC surface of 150°F. Increase this value by 10% as an allowance. Resulting base surface S/TC temperature = 265°F.

B. S/TC Inner Container

Using same ground rules as evaluation of experiments (3.5.1) and the following heat generation rate:

15,200 curies, 240 watts, 820 Btu/hr., 173,000 Btu/hr. ft.^{3}

Region I $T_0 - T_1 = [173{,}000/6(2.5)][1.25/12]^2 = 125°F$

Region II $T_1 - T_2 = [820/4\pi(2.5)][(12/1.25) - (12/2)] = 94°F$

Region III $T_2 - T_3 = [820/4\pi(2.5)][(12/2 - 1)] = 65°F$

1. The 265°F S/TC temperature is high by the 10% overpack temperature drop allowance. If Test D were used as a base:

   (Test D ΔT) X (power corrections) = comparative value

   91 (15,000/9,250) = 148°F

S/TC surface temperature @ 100°F ambient = 248°F, which is very close to the value obtained from the Test B results. Continue to use 265°F as maximum S/TC normal transport surface temperature, however.

2. Temperatures:

	r, in
$T_3 = 265°F$	12.0
$T_2 = 265 + 65 = 330°F$	2.0
$T_1 = 330 + 94 = 424°F$	1.25
$T_0 = 424 + 125 = 549°F$	0.0

3. T_0 is the centerline temperature; however, no structural member is at this temperature. As a conservative convenience, use T_0 as the capsule surface temperature. With this modification and rounding T_0 and T_1 to the nearest 5°F, the values above are the peak normal transport temperatures for the S/TC.

4. If 59.8 curies/watt were used, the heating would be:

15,000 curies, 251 watts, 856 Btu/hr., 181,000 Btu/hr. ft.^{3}
$T_3 = 100 + 173 = 273°F$
$T_2 = 273 + 68 = 341°F$
$T_1 = 341 + 98 = 439°F$
$T_0 = 424 + 131 = 570°F$

Sensitivity to deposited heat is low.

C. Overpack

1. Using Test B results, determine the maximum temperature drop from the S/TC surface to the inside surface of the WPJ:

$$\Delta T = 251 - 237 = 14°F \text{ @ } 235 \text{ watts}$$

The 251 and 237°F values are each averages of top, side, and bottom. Use 15°F for the maximum value (@ 240 watts).

2. A good value for the outside surface (O.S.) temperature of the Wooden Protective Jacket (WPJ) and Steel Shell cannot be obtained directly from the insolation test measurements because of the back heating, i.e., a value for the purpose of determining conductivity or steady state temperature condition associated with the internal heating load. However, a value can be obtained by examining data from the early (nonequilibrium) part of Test D which is provided in the following table:

TEMPERTURES (NOT NORMALIZED), °F

INSOLATION HEATING	WOODEN PROTECTIVE JACKET ON AMBIENT	ON O.S.[1]	OFF AMBIENT	OFF O.S.	STEEL SHELL ON O.S.	STEEL SHELL OFF O.S.
Day 2 Temp.	-	-	80	84	-	79
Δ	-		4			-1(0)
Day 3 Temp.	75	96	76	86.6	83	79
Δ	21		10.6		8	3
Day 4 Temp.	73	102	73	86	103	77
Δ	29		13		31	4
Day 5 Temp.[2]	71	101	74	87.5	103	79.5
Δ	30		13.5		32	5.5
Day 6 Temp.	73	102.6	-	-	106.5	-
Δ	29.7		-		33.5	-
Day 7 Temp.	69	101	-	-	101	-
Δ	32		-		32	-
Day 8 Temp.	71	100	-	-	102	-
Δ	29		-		31	-
Day 9 Temp.	72	102	-	-	104	-
Δ	30		-		32	-

[1] Outside surface
[2] Values following the fifth day did not change significantly

From the data above, the best reference estimated shell temperatures and differences from ambient are:

Power OFF	ΔT = 5°	T = 105°F
Power ON	ΔT = 30°	T = 130°F

The corresponding estimate for the outside surface of the WPJ is:

Power OFF	ΔT = 15° (To ambient)	T = 115°F
Power ON	ΔT = 30° (To ambient)	T = 130°F

To get a consistent set of maxima:

Ambient	100°F
Outside Shell Surface	135°F
Outside WPJ Surface	130°F

D. Summary values for Table 3.1.1, Maximum Package Temperature Under Normal Transport Conditions:

Outside Shell Surface	135°F	(57°C)
Outside WPJ Surface	130°F	(54°C)
Inside WPJ Surface	250°F	(121°C)
S/TC Surface	265°F	(129°C)
S/TC Shell Liner and Drum O.D. (Local Max.)	330°F	(165°C)
S/TC Drum Liner (Local Max.)	425°F	(218°C)
Source Capsule Surface	550°F	(288°C)

3.5.4 Maximum Internal Pressure

The maximum cavity pressure would result from heating air sealed in the gaps of the source chambers by closure of the covers. The cask is always loaded dry so that the only moisture would be vapor contained in air, which would also behave as a gas.

Several estimates of the maximum chamber pressure can be made:

Estimate 1 Upper Limit – The cask is sealed with source with the enclosed air at room (loading ambient) temperature of 70°F. Upon reaching equilibrium with the S/TC in the overpack, it is postulated that all of the air reached the maximum source surface temperature (550°F):

$P = [(550 + 460)/(70 + 460)]\ 14.7 = 28$ psia or 13.3 psig

The associated maximum stress would be a tangential (hoop) stress in the shell liner:

$\sigma = PD/2t = 13.3\ (8.25)/2(.1875) = 293$ psi, say 300 psi

Estimate 2 It is unlikely that all of the air enclosed within the S/TC could be heated to the source surface temperature. More plausible upper limit would be heating to the average temperature (maximum) of the drum sleeve based on the same type of calculation done for Estimate 1 above. Using the spatially averaged value of the maximum drum sleeve temperature determined in 3.5.5 of 312°F, the internal pressure maximum would be:

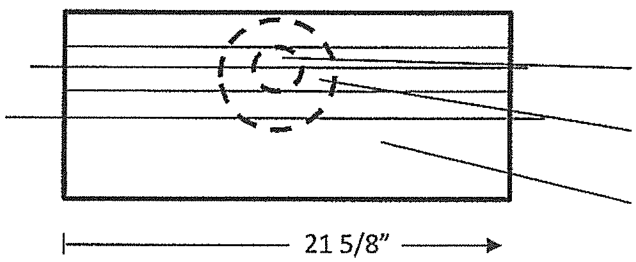
$P = [(312 + 460)/(70 + 460)]\ 14.7 = 21.4$ psia or 6.7 psig

And corresponding hoop stress 150 psi.

In either case, the stress levels are not significant in evaluating the integrity of the components.

3.5.5 Maximum Thermal Stress Temperatures

A. Drum Liner Average Temperature



From Table 3.1.1:

Peak Liner (local)	$T_1 = 425°F$
Drum Shell O.D. (local)	$T_2 = 330°F$
Drum End	$T_3 = 265°F$

The Space Weighted Average Temperature is taken as:

$$T_{av} = ({}_1T_2 \times {}_1W_2 + {}_2T_3 \times {}_2W_3)/({}_1W_2 + {}_2W_3)$$

Where ${}_1T_2$ is the linear average of T_1 and T_2, and ${}_1W_2$ is the corresponding weighting factor, in this case the one half length portion of the liner that can be considered within Region II. ${}_2T_3$ and ${}_2W_3$ are the corresponding values for the remaining one half length of the liner.

${}_1T_2 \times {}_1W_2 = (425 + 330)/2 \times 2 \text{ (in.)} = 756$

${}_2T_3 \times {}_2W_3 = (330 + 265)/2 \times 8.8 \text{ (in.)} = 2{,}622$

$= 3378/10.8 = 313°F$

B. Drum Shell (O.D.) Average Temperature

From Table 3.1.1:

Peak Temperature	$T_2 = 330°F$
Drum End	$T_3 = 265°F$

The mean temperature of the drum shells:

$$\Delta T = \overline{T} - \overline{T}_3 = \quad (1/(r_3 - r_2))\int_{r2}^{r3} T(r)dr$$

Where:

$$T(r) = T - T_3 = [q/4\pi K]\,[1/r - 1/r_3] = K_0\,[1/r - 1/r_3]$$

Substituting and integrating:

$$\Delta T = [K_0/(r_3 - r_2)][\ln r_3/r_2 - 1 + r_2/r_3]$$

$$= [820/4\pi 5][12/(12\text{-}2)][\ln 12/2 - 1 + 2/12] = 15°F$$

The maximum space averaged temperature of drum shell = 265°F + 15 = 280°F

C. Shell Liner Average Temperature

The space averaged maximum temperature of the shell assembly liner is essentially the same as that of the drum shell (OD) because they are concentric and in intimate contact.

$$T_{av} = 280°F$$

Under the same conditions, the average shell temperature is 265°F. The important value from the thermal stress standpoint is the T between shell and liner. This T = 15°F and is not likely to vary much.

D. Summary of compatible maximum space average component temperatures for thermal stress calculations:

Drum Liner	313°F	
		ΔT = 33°F
Drum O.D.	280°F	
Shell Assembly Liner	280°F	
		ΔT = 15°F
Shell O.D.	265°F	

The above represents the most severe combination of thermal gradients anticipated under normal transport conditions.

3.5.6 Hypothetical Accident – Fire Test

A. Adiabatic Temperature Rise Rate of S/TC

	Weight, Pounds			
	Lead	Steel	Tung. Alloy	Total
Shell Assembly	2,340	414	-	2,754
Drum (lead)	242	56	-	298
Covers (2)	72	45	-	117
International Capsule (with plugs and sleeves)	-	10	38	48
AECL Drawer	29	8	neg.	37
Long Plug and Sleeve	-	8	42	50
	2,683	541	80	3,304
Cp, Btu/lb. °F	.0315	.118	.032	
Heat Capacity, Btu/°F	85	63	2.6	151 B/F

15,000 curies 240 watts = 820 Btu/hr.

Adiabatic Temperature Rise Rate = $\frac{820.3}{151}$ = 5.43°F/hr.

B. Maximum Overpack Backface Temperature

Ref: W. H. Lake, "Thermal Analysis of Packaging Using the Integral Method," Proceedings of the Seventh International Symposium on Packaging and Transportation of Radioactive Materials, New Orleans, 1983 (PATRAM 83)

Calculate the adiabatic equilibrium temperature associated with the post fire cool down condition as representative of the upper limit of the backface overpack (WPJ) temperature. No credit taken for the steel shell.

The initial conditions and thermal properties:

t_f = fire duration = one half hour
T_0 = fire temperature (outside temperature) = 1,475°F
T_i = initial overpack temperature, taken as the average WPJ temperature at the maximum package temperature conditions under normal transport (Table 3.1.1) = (1/2)(140 + 245) = 193°F
ℓ= Wooden Protective Jacket (WPJ) wall thickness = 6 in. = 0.5 ft.
k = thermal conductivity of WPJ
= 0.085 B/hr. ft. °F (from APA Applications Summary, Page 13)
= WPJ density = 36 lbs./cu. Ft. (measured value)
C_p= heat capacity = 0.65 B/LB°F (Marks IV, Page 300, Table 9)
= thermal diffusivity = $K/\rho C_p$ = 0.085/36(0.65) = 0.00363 ft.$_2$/hr.

To calculate the post fire adiabatic equilibrium temperature, T, when the radiation source temperature is specified, use is made of the different geometry and boundary condition cases worked out in Table 3 of the reference to obtain an equivalent heat flux. Only constant heat flux solutions are available for the cylindrical and spherical geometry cases. However, the semi-infinite slab geometry, for which both constant temperature and constant heat flux solutions are available, is used to develop a constant heat flux equivalent to the imposed constant temperature condition. The equivalent heat flux is used to obtain cylindrical and spherical geometry solutions. The adiabatic temperature rise, $T = T - T_i$, where the subscript designates the particular case, using the nomenclature of the reference.

1. Semi-Infinite Slab, Constant Surface Temperature

$T_{x2} = (6/\ell)\ (\alpha t_f/24)^{1/2}\ (T_0 - T_i)$ ref. equ. 27

$= (6/0.5)\ [(0.0036)\ (0.5)/24]^{1/2}$ (1282)

$=$ 133°F

2. Semi-Infinite Slab, Constant Heat Input

The equivalent constant heat input is obtained from this case using the temperature rise calculated from the previous constant temperature case.

$\Delta T_{x3} = (q_0\ \alpha t_f)/(k\ell)$ ref. equ. 28

$q_0 = \Delta T k\ell/\alpha t_f$

$=$ (133) x (0.085) (0.5)/(0.00353) (0.5) = 3114 Btu/hr. ft.^{2}

3. Infinite Cylinder, Constant Heat Input

$T_c = (2\ q_0\ R_0\ \alpha t_f)/(k(R_0^2 - R_1^2))$ ref. equ. 29

$= (2(3114)\ (1.833)\ (0.00363)\ (0.5)]/[0.085(1.833^2 - 1.333^2)]$

= 154°F

4. Sphere, Constant Heat Input

$\Delta T_s = (3\ q_0\ R_0^2\ \alpha t_f)/(k(R_0^3 - R_1^3))$ ref. equ. 30

$= (3(3114)\ (1.833)^2\ (0.00363)\ (0.5)]/[0.085(1.833^3 - 1.333^3)]$

= 177°F

The Wooden Protective Jacket is 45 inches high and 44 inches in outside diameter and is probably better represented by a sphere than by an infinite cylinder. The spherical values are used for evaluating the temperature rise using the inside and outside diameters of the Wooden Protective Jacket as the inside and outside diameters of the equivalent sphere.

The peak backface temperature, T_{BF} = peak inside wall temperature of the Wooden Protective Jacket is less than, but for the present purpose, taken equal to the adiabatic equilibrium temperature, T_{AE}

$$T_{BF} = T_{AE} = 193 \text{ (initial)} + 177 \text{ (adiabatic rise)} = 370°F$$

C. Peak S/TC Temperature

The peak S/TC surface temperature is equal to the peak backface temperature plus the drop (15°F) needed to transfer internal heat generated through the space between overpack and S/TC.

$$T \text{ (S/TC surface, post fire maximum)} = 370 + 15 = 385°F$$

The peak temperatures for the S/TC become:

o S/TC surface	385°F	(196°C)
o S/TC shell liner and drum O.D. (local max.)	450°F	(232°C)
o S/TC drum liner (local max.)	545°F	(285°C)
o Source capsule surface	670°F	(355°C)

These temperatures are unlikely to be reached because the S/TC is unlikely to remain adiabatic for 22 hours (120°F/5.43°F/hr.) after the termination of the fire. Nevertheless, making the evaluation of the consequence of the hypothetical accident on this basis: (1) there would be no lead melting; the peak lead temperature is less than 545°F (the maximum local lead temperature is lower than the local maximum temperature of the drum liner) as compared with a melting point of 618°F; and, (2) the maximum source capsule surface temperature (355°C) remains well below the weld sensitization temperature (above 480°C).

It is not crucial to the integrity of the packaging if either of the criteria employed above are exceeded. However, they provide a convenient and conservative measure for evaluation of maximum normal and upset conditions.