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PIQUA-ELK RIVER REACTORS
SPENT FUEL SHIPPING CASK

FINAL DESIGN REPORT

Submitted By

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SECTION I

Introduction And Summary

INTRODUCTION

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Introduction

This design report along with referenced drawings describes the Piqua-Elk River Spent Fuel Shipping Cask. The cask is designed to transport 19 spent fuel assemblies from either reactor to their respective reprocessing plants. Rail shipment has been selected as the normal mode of transport; however, it is possible to ship the cask by truck with special equipment and special permits from applicable highway authorities over the selected route of travel. The cask design and construction are described in the following drawings.

Drawing Number

Drawing Title

F-2096	General Assembly
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C-1575	Thermocouple Assembly
B-1018	Bellows Seal Globe Valve

To assist in the evaluation of the cask design, technical data for the fuel used in the design of the cask is tabulated below. These data have been supplied by AEC-COO and are contained in the following documents:

Piqua

Atomics International System Description No. A87-710-1
AEC-COO Form 434 dated July 8, 1960
PNRF Final Safeguards Summary NAA-SR-5608

Elk River

ACNP Final Physics Report dated May 23, 1960
ACNP Start-Up Physics Report dated September 30, 1960
AEC-COO Form 434 dated July 8, 1960
ERR Final Hazards Report dated July 8, 1960.

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Introduction (Continued)Fuel Assembly Data

<u>Characteristic</u>	<u>Piqua</u>	<u>Elk River</u>
Overall Length - inches	80-1/2	81-5/8
Overall Cross-Section - Inches	5-9/16	3-19/32
Active fuel length - inches	54	60
Cross-section-fuel area - inches	5.210 dia.	3.450 sq.
Fuel element configuration	Concentric Cylinders	5x5 Array of fuel pins
Cladding Material	Al	SST
Cladding dimensions - inches	0.035 thk.	.452 OD x .020 wall
Fuel Material	U-Al	UO ₂
Enrichment in U-235 w/o	1.94	4.3
Fuel loading per assy - KG U-235	1.58	1.16
No. of Assy per Core	85	148
Core power - MW	45.5×10^6	58.2×10^6
Average Thermal Flux	1.4×10^{13}	1.32×10^{13}
Radial Peaking Factor	1.47	1.45*
Axial Peaking Factor	1.47	1.72*
Operating time - days	515*	640
Decay Time prior to Shipment - Days	120	120
Fuel Assy Ref. Dwg.	7537-71801	12D02000

*Based on 275 MWD/Element Burnup

*Verbal Communication - A/C

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SUMMARY

A. CASK SYSTEM DESCRIPTION

The Piqua-Elk River Spent Fuel shipping cask is designed to transport 19 fuel assemblies from either reactor starting 120 days after reactor shutdown for re-fueling. The maximum weight of the loaded cask is 30 tons. The maximum weight of the loaded cask with shipping structure is 32 tons. The overall cask dimensions are 55" dia. x 108" high. The space envelope required for the cask and shipping structure is 7 ft wide by 10 ft long by 10 ft high. Since the equipment airlocks at both the Piqua and Elk River reactor plants require that the cask enter and leave the containment shell in horizontal position, special handling equipment is included for these operations.

The cask system is designed to meet all the requirements of 10 CFR 72 and ICC regulations. Cask design approval under 10 CFR 72 will be obtained. Also, Bureau of Explosives approval will be obtained and a permit number assigned to the cask.

The cask system is composed of six major components. These include the cask body, closure head, fuel basket, shipping structure, lifting yoke, and Elk River fuel assembly adapters. Internal surfaces that can become contaminated and cannot be painted have been specified as stainless steel. All external surfaces of the cask which can be adequately painted and maintained are specified as carbon steel. Carbon steel surfaces are painted with a special "MARASET" epoxy paint which has a particular resistance to strong organic solvents. Components on which there is considerable work during loading and unloading, such as closure flanges, drain valves, vent valves, accessories, etc., are also stainless steel since maintenance of painted surfaces in these areas is impractical.

The cask body consists of cylindrical outer and inner shells with the annulus between the shells filled with lead shielding. The lead shielding is bonded to inner and outer shells to improve structural integrity and provide maximum heat transfer efficiency. Cooling fins are welded to the outer shell to dissipate decay heat to the surrounding air. The cask inner and outer bottom heads are flanged-only heads with rounded corners to eliminate corners welds. The cask body top plate is solid stainless steel and is welded to the lower closure flange and outer shell. Two sets of trunnion sockets are provided on the cask outer shell for handling the cask in both vertical and horizontal positions. The upper set is designed to receive the special lifting yoke and carry the cask in the vertical position or permit rotating the cask from vertical to horizontal position. The lower set is designed to mate with trunnions on the cask dolly, which is used at the reactor plants for moving cask through the equipment airlocks.

The closure head consists of flat cylindrical plates welded to a flanged and dished carbon steel head. The closure flange is welded to this subassembly. Internal supports are welded inside the head to enable the cask to withstand

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Cask System Description (Continued)

required impact on the closure head. The closure head is bolted to the cask body by 24 high strength stainless steel studs. Locating pins permanently installed in the cask body guide the closure head on to the cask body and prevent stud damage. A stainless steel accessory cavity is provided in the top of the closure head to contain and protect cask instrumentation and fittings.

The fuel basket is an aluminum cylinder in which 19 cavities have been machined to receive the fuel assemblies. These cavities are dimensioned to directly receive the Piqua fuel assemblies. However, to carry the Elk-River fuel assemblies, a set of adapters is required. In both cases clearances are minimized to improve heat transfer from the fuel. The basket material is specified as 6061 -0 aluminum with a nominal addition of one w/o Cadmium for criticality control. Aluminum is used because of its high thermal conductivity and coefficient of thermal expansion. The outside diameter of the basket has been calculated so that at operating temperature the differential thermal expansion between the basket and cask body closes the gap between the basket and shell -- thus efficiently carrying the heat from the basket to the cask body. In the cold condition, this differential expansion allows sufficient clearance for basket removal and replacement.

The adapters required to carry Elk-River fuel assemblies are also made of aluminum and are machined to fit the basket cavity as close as possible without affecting ease of removal and replacement. These adapters are square internally to fit the Elk River fuel assemblies as close as possible for both efficient heat transfer and fuel assembly support.

The shipping structure consists of a base fabricated from structural steel shapes and two "A" frames on the fore and aft axes of the cask. The "A" frames are designed to transmit the lateral loads encountered during transport from the top of the cask into the base and in turn to the vehicle bed. Support rings on the cask bottom and base transmit lateral loads from cask bottom to vehicle bed. In order to prevent concentration of the entire cask load in the center of the base, the base structure is designed so that the "A" frames can be placed under load prior to shipment by shimming underneath the corners of the shipping structure. This in effect pre-stresses the "A" frames and insures that the cask load is spread over the full area of the base on the transporting vehicle.

The cask lifting yoke is a "C" shaped structure consisting of two parallel flat plates with two trunnions which engage the cask trunnion sockets. This permits the cask to rotate while supported from the lifting yoke. The lifting yoke is adequate for handling the cask alone or the cask and shipping structure combined. This capability facilitates handling the cask and shipping structure at both reactor sites.

The cask system is provided with accessories and instrumentation required to safely load, transport and unload the cask. Special 3/4" nuclear type packless drain and vent valves are provided for draining, venting and sampling operations.

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Cask System Description (Continued)

These valves are manufactured of stainless steel with Teflon discs, and are rated 400 psi and at 400°F. The vent valve is located in the accessory cavity in the head where it is protected by the accessory cavity cover plate. The drain valve is located at the bottom of the outer shell and is protected by 1/2" stainless steel enclosure. Both drain and vent valves are equipped with stainless steel snap-tite series "H" quick disconnect couplings. This particular coupling has been selected because of its ability to maintain a seal during coupling and uncoupling operations. Also included in the accessory cavity in the closure head is a 0-100 psi pressure gage and a rupture disc assembly. The pressure gage is a special shock resistant, weather-proof design with corrosion resistant internals. The gage is capable of complete immersion in water without affecting its operation. The rupture disc assembly consists of stainless steel flanges and an aluminum disc rated at 75 psi. A vent hole is provided through the accessory cavity cover plate so that if the rupture disc should blow, sufficient opening is provided from the accessory cavity to exhaust the air or vapor released from the rupture disc. Four thermocouple receptacles are provided in the cask body to permit measurement of cask innershell temperature. The sensitive end of the thermocouple tube containing the iron-constantan thermocouple is brazed to the cask innershell. Aluminum thermocouple receptacles are attached to welded bosses in the outer shell at the upper end of the cask body.

Since the cask is designed for dry shipment at atmospheric pressure, no filter is provided on the pressure relief device (rupture disc). The filter is not required because there is only one conceivable situation in which the rupture disc could blow and that is in the case of a fire. Even in this case it is possible that the rupture disc would not blow unless the fire was so concentrated that the rupture disc assembly was directly exposed to the full effect of the flames. In such a case the effectiveness of a filter on the rupture disc would be doubtful and therefore provision of a filter unit is of doubtful value. However, should liquid coolants ever be used in the cask with the associated possibility of pressurized operation, a filter unit will be installed on the cask.

An Iodine removal device has not been provided on the cask because the total iodine inventory in the cask is such that complete release of all free I-131 would not exceed 10 curies (see misc. calculations). This is based on assuming that 33% of the total I-131 would be released from the fuel in the event of complete cladding failure of all elements. This is a sufficiently conservative assumption to eliminate any further consideration of the need for iodine control.

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B. STRUCTURAL INTEGRITY

The cask is designed to provide maximum structural integrity and meet all requirements of 10 CFR 72 and ICC regulations. Examination of the cask drawings will show that every attempt has been made to eliminate sharp corners and large projections where forces encountered in accident conditions could cause stress concentration and failure. Also, location and geometry of main structural welds is such that they are not located in high-stress areas. The closure head has been specifically designed so that impact forces resulting from possible shipping accidents will tend to be glancing blows rather than direct forces normal to the surface. This minimizes the possibility of structural failure of important cask components.

The closure head is bolted to the cask through 24 high-strength stainless steel studs. These studs pass through heavy stainless steel closure flanges which are welded to the cask body and head. The minimum external plate thickness used in the closure head and cask body is 1". The minimum innerplate thickness is 1 1/2". The inner and outer shells of both cask body and closure head are bonded to the lead shielding to provide additional structural integrity. To allow for the differential expansion between the steel shield envelope and the lead shielding under normal operating conditions, a small expansion space in the cask body and closure head is provided. The cask is designed for an internal pressure of 100 psi even though the normal operating pressure will be nominally atmospheric pressure.

The cask regarded as a simple beam is adequate to withstand 10 G's. It is also adequate to withstand a 15 foot free fall on a flat surface normal to the side, top or bottom without rupture of the shield envelope or failure of the cask closure. The closure design is adequate to withstand forces in any direction equal to 60 times the weight of the head and 15 times the weight of the loaded cask. The 1" minimum outer shell thickness provides the required resistance to piercing. Based on comparison of this cask design with the cask which has been tested by AEC and results reported in TID-7651 it is believed that this cask has additional structural integrity beyond that required by 10 CFR 72.

The shipping structure and method of attachment to the cask and transport vehicle are designed to withstand loads of 10 G. in any horizontal direction and 2 G's in the vertical direction. The shipping structure base is designed so that the entire weight of the cask is not concentrated in the center of the vehicle bed but is spread over the full area of the base. This is done by placing shims under the four corners of the base prior to shipment, thus pre-stressing the shipping structure "A" frames and removing some of the load in the center of the shipping structure base. This operation will be specifically covered in the detailed loading and unloading procedures.

The cask lifting yoke, trunnion sockets and closure head liftings lugs and cables are designed to safely withstand 6 times the actual load. This provides the required safety during cask handling operations. To minimize the possibility of

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damage to cask instrumentation and accessories, these components are protected by steel cover plates. Specifically the components located in the accessory cavity in the closure head are covered by a 3/4" thick steel plate which is bolted to the closure head and lockwired. The drain valve is protected by a welded stainless steel closure of 1/2" thick plate. The cover for this enclosure is also bolted and lockwired to the cask. To minimize the possibility of unauthorized tampering with these important cask components during transport, a lead seal along with lockwiring is placed on the bolts which hold the cover plates in place.

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PIQUA - ELK RIVER REACTORS SPENT FUEL SHIPPING CASK SHIELDING CALCULATIONS

I BASIC DATA

<u>ITEM</u>	<u>PIQUA</u>	<u>ELK RIVER</u>
REACTOR POWER - WATTS	45.5×10^6	58.2×10^6
OPERATING TIME - DAYS	515 *	640 Δ
LOAD FACTOR	100%	100% Δ
FUEL ASSY COOLING TIME - DAYS	120 (MIN)	120 (MIN) Δ
RADIAL PEAKING FACTOR	1.47	1.45 Δ
AXIAL PEAKING FACTOR	1.47	1.72 Δ
FUEL ASSEMBLIES PER CORE	85	148
ACTIVE LENGTH OF FUEL	54"	60"
ACTIVE CORE DIAMETER	58.2"	60"
REF DWGS	7537-71801	12D0200

NOTES:

1. PIQUA DATA FROM AI SD NO. A87-710-1
AND USNEC FORM 434 DATED 7/8/60

2. ELK RIVER DATA FROM PHYSICS REPORT DATED
5/23/60 AND USNEC FORM 434 DATED 7/8/60

* BASED ON 275 MW/ELEMENT (HAZARD REPORT PAGE I-3)

REFERENCE:
W-3100

PIQUA-ELK RIVER SPENT FUEL SHIPPING CASK

KNAPP MILLS INCORPORATED
FOOT OF WEST ST. WILMINGTON, DEL.

SHIELDING
ANALYSIS

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II. POWER DENSITY CALCULATION

SINCE SHIELD CALCULATIONS WILL BE BASED ON LINE SOURCE GEOMETRY NEGLECTING SELF-ABSORPTION, REACTION POWER IN W/CM OF FUEL ELEMENT, IS REQUIRED

$$\text{PIQUA} \quad \frac{455 \times 10^6}{(85)(54)(254)} = 3900 \text{ W/CM LENGTH}$$

$$\text{ELK RIVER} \quad \frac{582 \times 10^6}{(148)(60)(254)} = 2580 \text{ W/CM LENGTH}$$

IT APPEARS THAT THE PIQUA FUEL WILL BE LIMITING FOR SHIELDING DESIGN

III. GAMMA SOURCE & SPECTRUM CALCULATION - PIQUA

USE DATA COMPILED IN AEC-R-5216 APPENDIX F *

$$S_L = \left(\frac{\text{MEV}}{\text{SEC-WATT}} \right) \left(\frac{\text{WATT}}{\text{CM}} \right) \div \left(\frac{\text{AVG MEV}}{\gamma} \right) = \gamma/\text{CM}$$

GROUP	MEV/SEC-WATT	W/CM	MEV/γ	S _L - γ/CM-SEC
III	1.1 × 10 ⁸	3900	1.2	3.58 × 10 ¹¹
IV	2.2 × 10 ⁷		1.6	5.36 × 10 ¹⁰
V	4.2 × 10 ⁷		2.0	8.18 × 10 ¹⁰
VI	4.8 × 10 ⁶		2.5	7.49 × 10 ⁹
VII	3.0 × 10 ⁵		3.5	2.48 × 10 ⁸

NEGLECT GROUPS I & II FOR SHIELDING PURPOSES

* FOR T₀ = ∞ T_S = 120 DAYS

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IV ANALYTICAL MODEL

THE FUEL ASSEMBLIES WILL BE ARRANGED IN A CYLINDRICAL BASKET IN THE CASK. PRELIMINARY LAYOUTS INDICATE POSSIBLY 24 ASSEMBLIES MAY BE CARRIED IN THE CASK. HOWEVER, SINCE THE INTERNAL ARRANGEMENT IS NOT FIRM, SHIELDING REQUIREMENTS FOR ONE ASSEMBLY CAN BE CALCULATED AND THESE RESULTS USED TO ESTIMATE SHIELD THICKNESSES FOR VARIOUS ARRANGEMENTS OF FUEL ASSEMBLIES.

FOR TOP AND BOTTOM SHIELD CALCULATIONS A VOLUME SOURCE STRENGTH WILL BE REQUIRED. THIS IS COMPUTED AS FOLLOWS FOR PIQUA.

<u>GROUP</u>	<u>S_L %/CM</u>	<u>$\div$ ELEMENTS / AREA</u>	<u>$= S_V$ %/CM³-SEC</u>
<u>III</u>	2.58×10^{11}	137 CM ²	2.60×10^9
<u>IV</u>	5.26×10^{10}		3.90×10^8
<u>V</u>	8.18×10^{10}		5.95×10^8
<u>VI</u>	7.49×10^9		5.44×10^7
<u>VII</u>	2.48×10^8		1.80×10^6

KADANE SHIELD MODEL

EQUATION FOR THE FLUX FROM A LINE SOURCE

$$\phi = \frac{BS_L}{2\pi a} [F(\theta, b)] K_e$$

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B = BUILD-UP FACTOR

S_L = LINE SOURCE STRENGTH r/cm

a = SOURCE TO DOSE POINT DISTANCE

$F(\theta, b)$ = TABULATED FUNCTIONS

K_E = FLUX TO DOSE CONVERSION FACTOR

ASSUME $a' = \text{APPROX } 15'' \text{ MIN (INCLUDING CRACK FINS)}$

$$\theta = \tan^{-1} \frac{27}{133} = 12.7^\circ$$

$$\theta' = \tan^{-1} \frac{27}{15} = 63.4^\circ$$

CHECK TO DETERMINE WHETHER 10 MR/HR @ 3 METERS
OR 200 MR/HR ON CONTACT IS LIMITING. EVALUATE
EQUATION AT APPROX 9" LEAD SHIELD AND SCALE
UP 10 MR/HR TO ON-CONTACT.

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$$D_c = 10 \left(\frac{1.33}{15} \right) \left(\frac{6 \times 10^{-6}}{3.5 \times 10^{-6}} \right) = 152 \text{ MR/HR}$$

DOSE RATE AT 3 METERS WILL BE LIMITING.
THIS APPLIES TO ALL ARRANGEMENTS OF FUEL ASSEMBLIES SINCE THE DISTANCE EFFECT TO OTHER FUEL ASSEMBLIES IS LESS AND THE SLANT PATH SHIELD THICKNESS GREATER. BOTH THESE EFFECTS COMBINE TO REDUCE THE ON-CONTACT DOSE RATE RELATIVE TO THE DOSE RATE AT 3 METERS. CONTINUE ANALYSIS FOR 10 MR/HR AT 3 METERS.

V SHIELD CALCULATIONS (RADIAL)

ASSUME 8" Pb LEAD SHIELD $t = 20.3 \text{ cm}$

<u>GROUP</u>	<u>μ_{pb}</u>	<u>b</u>	<u>B</u>	<u>SL</u>	<u>$F(\theta, b)$</u>	<u>K_E</u>	<u>DOSE - MR/HR</u>
III	0.68	13.8	5.0	3.58×10^{10}	2.0×10^{-7}	2.1×10^{-3}	0.35
IV	0.56	11.4	5.0	5.36×10^{10}	2.3×10^{-6}	2.6×10^{-3}	0.76
V	0.51	10.3	5.0	8.18×10^{10}	7.0×10^{-6}	3.1×10^{-3}	4.19
VI	0.48	9.75	5.0	7.49×10^9	1.2×10^{-5}	3.6×10^{-3}	0.76
VII	0.46	9.35	5.1	2.48×10^8	1.65×10^{-5}	4.6×10^{-3}	0.04
TOTAL							6.10 MR/HR

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ASSUME $9\frac{1}{2}^N$ Pb LEAD SHIELD - $t = 24.1$ CM

GROUP	b	B	S_L	$F(\theta, b)$	K_E	Dose - MR/HR
III	16.4	5.6	3.58×10^{11}	145×10^{-8}	21×10^{-3}	0.029
IV	13.5	5.7	5.36×10^{10}	27×10^{-7}	26×10^{-3}	0.101
V	12.3	5.8	8.18×10^{10}	9.1×10^{-7}	3.1×10^{-3}	0.631
VI	11.6	5.9	7.49×10^9	1.8×10^{-6}	3.6×10^{-3}	0.135
						<u>0.896 MR/HR</u>

PLOT STRAIGHT LINE ON SEMI-LOG PAPER AND USE CURVE TO ESTIMATE SHIELDING FOR VARIOUS FUEL ASSEMBLY INTERNAL ARRANGEMENTS

VI APPLY RESULTS TO INTERNAL ARRANG'S

CONSIDER A 19 ASSEMBLY CASK WITH THE FUEL ASSEMBLIES ARRANGED IN TWO CONCENTRIC CIRCLES AND ONE IN CENTER. THE FUEL ASSEMBLIES WILL BE CARRIED IN A SOLID ALUMINUM BASKET WITH APPROX 6" CENTER TO CENTER SPACING

MAKE SCALE LAYOUT AS ABOVE AND DETERMINE SLANT PATH PENETRATION DISTANCES IN LEAD SHIELD AND ALUMINUM

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Dose Rate - mR/hr

Dose Rate vs. Shield Thickness
ONE T-1 QUA - FUEL ASSEMBLY
 $T_0 = \infty$ $T_8 = 120$ DAYS LOAD FACT. 100%
RADIAL & AXIAL PEAKING FACTOR = 1.0

SHIELD THICKNESS - INCHES OF LEAD

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BASKET. SCALE LAYOUT SHOWN ON PAGE 9. TWO DOSE POINTS ARE CONSIDERED. NEGLECT ABSORPTION IN ELK- RIVER FUEL ASSEMBLIES BUT INCLUDE ABSORPTION BY ALUMINUM BASKET. .

Dose AT P₁ - NOMINAL 8³/₄" EQUIV LEAD SHIELD

FUEL ASSY	AL THICK	STEEL THICK	LEAD THICK	STEEL THICK	TOTAL EQUIV LEAD	* DOSE † RATE
c	.75	.50	8.12	1.00	9.09	1.60
d	.75	.50	8.12	1.00	9.09	1.60
b	1.50	.60	9.12	1.10	10.38	0.37
e	1.50	.60	9.12	1.10	10.38	0.37
a	4.50	.75	10.25	1.21	12.33	0.03
f	4.50	.75	10.25	1.21	12.33	0.03
l	1.40	.50	8.12	1.00	9.24	1.22
h	1.40	.50	8.12	1.00	9.24	1.22
g	11.2	.55	8.45	1.05	12.83	0.02
J	11.2	.55	8.45	1.05	12.83	0.02
K	12.3	.50	8.00	1.00	11.59	0.06

6.54 mR/hr

Dose AT P₂

c	.75	.50	8.00	1.00	8.91	1.77
b	1.00	.60	8.55	1.10	9.70	0.68
d	1.00	.60	8.55	1.10	9.70	0.68
a	2.75	.70	8.80	1.20	10.45	.25
e	2.75	.70	8.80	1.20	10.45	.25
f	2.20	.75	10.40	1.20	11.96	.03
L	2.20	.75	10.40	1.20	11.96	.03
h	1.90	.50	8.10	1.05	9.35	1.08
l	3.50	.55	8.25	1.05	9.90	.53
g	4.40	.60	8.45	1.05	10.34	.30
K	2.80	.50	8.00	1.00	9.43	.94

6.54 mR/hr

† FROM CURVE PAGE 7 * AT 2 MEV

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1/2" STEEL

RENSED SCALE LAYOUT
49" O.D. x 30" I.D.

P₂

W-3100 SHIELDING
CALCULATIONS
PAGE 3 REV 1

P₂

THESE RESULTS INDICATE THAT THERE IS NO SIGNIFICANT DIFFERENCE BETWEEN THE TWO DOSE POINTS.

CONSIDERING THAT THE CORE CAN BE LOADED WITH 19 ELEMENTS FROM THE HOTTEST REGION IN THE CORE, THE MAXIMUM DOSE RATE IS:

$$D = (6.54)(1.47) = 9.6 \text{ MR/HR} \quad \text{MR} < 10 \text{ MR/HR}$$

IN THE CASE OF THE ELK RIVER ELEMENTS, SINCE THE POWER DENSITY IS LOWER AND THE ELEMENT WILL BE SURROUNDED BY AN ALUMINUM ADAPTER, THE MAXIMUM DOSE RATE WILL BE LESS THAN FOR THE PIGON CASE.

IN BOTH CASES, USING LINE SOURCE GEOMETRY, NEGLECTING SELF-ABSORPTION AND USING SOURCE STRENGTH DATA FOR INFINITE LATH IN AT FULL POWER, PROVIDES THE NECESSARY SAFETY MARGIN WITH RESPECT TO SHIELDING. THEREFORE THE 8 3/4" EQUIVALENT LEAD RADIAL SHIELD IS ADEQUATE.

THIS SHIELD WILL BE COMPOSED OF 1/2" STEEL INNER SHELL 8" OF LEAD AND 1" STEEL OUTER SHELL. THE 19 FUEL ASSEMBLIES WILL BE ARRANGED IN APPROXIMATELY A HEXAGONAL ARRAY IN A 30" DIAMETER ALUMINUM CYLINDER.

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VII TOP & BOTTOM SHIELD MODEL

TO CALCULATE THE SHIELD THICKNESS FOR THE TOP AND BOTTOM OF THE CASK, A CYLINDRICAL SOURCE EQUIVALENT TO 19 FUEL ASSEMBLIES WILL BE USED. ACTUALLY, THE 19 FUEL ASSEMBLIES ARE SPREAD OUT IN THE 50" DIA ALUMINUM BASKET WHICH WOULD BE MORE CLOSELY APPROXIMATED BY 19 COLLIMATED SOURCES DIRECTED VERTICALLY UPWARD AND DOWNWARD. THIS CONDITION IS DIFFICULT TO DESCRIBE ANALYTICALLY WITHOUT COMPLEX METHODS NOT JUSTIFIED IN CASK DESIGN, THE CYLINDRICAL MODEL EQUIVALENT IS A CONSERVATIVE APPROXIMATION OF THE ACTUAL CASE.

THE SOURCE STRENGTH IN PIQUA ELEMENTS IS HIGHER THAN ELK KIVEIK, HOWEVER, THE SELF-ABSORPTION IN PIQUA ASSEMBLIES WILL BE GREATER DUE TO THE SOLID U-AL CYLINDRICAL FUEL COMPARED TO THE 5XS PIN ARRAY IN ELK KIVEIK ELEMENTS. THEREFORE TO ASSURE A SHIELD ADEQUATE FOR BOTH CASES, THE PIQUA SOURCE STRENGTH WILL BE USED IN A CYLINDER EQUIVALENT TO 19 ELK KIVEIK ASSEMBLIES.

DETERMINE EQUIVALENT CYLINDER RADIUS

$$R = \sqrt{\frac{(19 \times 3.75)^2}{\pi}} = 9.22" = 23.4 \text{ CM}$$

CALCULATE SELF-ABSORPTION COEFFICIENTS.

REFERENCE:

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$$\text{WEIGHT SST } (25)(.452^2 - .412^2) \frac{\pi}{4} (2.54)^2 7.9 = 34.0 \text{ GR.}$$

$$\text{WEIGHT UO}_2 (25)(.407)^2 \frac{\pi}{4} (2.54)^2 9.5 = 199 \text{ GR}$$

$$\text{VOLUME OF CROSSSECTION - 1 CM LONG } (3.75^2)(2.54)^2 = 90.6 \text{ CM}^3$$

$$\rho_{\text{UO}_2} = \frac{199}{90.6} = 2.19 \text{ G/CM}^3$$

$$\rho_{\text{SST}} = \frac{34}{90.6} = .375 \text{ G/CM}^3$$

	<u>UO₂</u>			<u>SST</u>			<u>TOTAL</u>
GROUP	<u>ρ</u>	<u>μ/ρ</u>	<u>μ_s</u>	<u>ρ</u>	<u>μ/ρ</u>	<u>μ_s</u>	<u>$\mu_s \text{ cm}^2$</u>
III	2.19	.063	.138	.375	.051	.019	.157
IV	"	.051	.112	"	.044	.017	.129
V	"	.047	.103	"	.041	.015	.118
VI	"	.044	.096	"	.037	.014	.110

EQUATION FOR THE FLUX

$$\phi = \frac{BS_v}{2\mu_s} \left[E_2(b_1) - \frac{E_2(b_1 \sec \theta)}{\sec \theta} \right] K_e$$

ASSUME $a_1 = \text{APPROX } 19''$

$$R_0 = 23.4 \text{ CM}$$

$$\theta = \tan^{-1} \frac{23.4}{34.8} = 3.85^\circ$$

$$\theta_1 = \tan^{-1} \frac{23.4}{48.3} = 25.9^\circ$$

REFERENCE:

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FOR ANGLES SMALLER THAN 5° , THE FLUX MAY BE CALCULATED USING THE FOLLOWING EQUATION

$$\phi = \frac{BS_v \pi R_o^2}{M_s} \frac{e^{-b_1}}{4\pi a^2} K_E = \frac{R_o^2}{4a^2} \frac{BS_v e^{-b_1}}{M_s} K_E$$

VIII SHIELD CALCULATION

ASSUME 8" Pb = 20.3 CM

GROUP	b	B	S_v	M_s	e^{-b_1}	K_E	DOSE RATE
III	13.8	5	2.60×10^9	.157	1×10^{-6}	2.1×10^{-3}	.197
IV	11.4	5	3.90×10^8	.129	1.1×10^{-5}	2.6×10^{-3}	.489
V	10.3	5	5.95×10^8	.118	3.35×10^{-5}	3.1×10^{-3}	2.56
VI	4.75	5	5.44×10^7	.110	5.8×10^{-5}	3.6×10^{-3}	.583
TOTAL							4.23 mR/hr

ASSUME 7" Pb = 17.75 CM

GROUP	b	B	S_v	M_s	e^{-b_1}	K_E	DOSE RATE
III	12.05	4.6	2.60×10^9	.157	5.8×10^{-6}	2.1×10^{-3}	1.05
IV	9.95	4.5	3.90×10^8	.129	4.8×10^{-5}	2.6×10^{-3}	1.92
V	9.05	4.5	5.95×10^8	.118	1.2×10^{-4}	3.1×10^{-3}	9.54
VI	8.52	4.5	5.44×10^7	.110	2.1×10^{-4}	3.6×10^{-3}	1.90
TOTAL							14.41 mR/hr

PLOT STRAIGHT LINE ON SEMI-LOG PAPER

REFERENCE:

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Dose Rate - MR/HR

DOSE RATE VS. SHIELD THICKNESS
19 ELK RIVER FUEL ASSEMBLIES
 $T_0 = 10$ $T_5 = 120$ DAYS LOAD FACTOR = 100%
Radial & Axial Peaking Factors = 1.0

SHIELD THICKNESS - INCHES OF LEAD

IX APPLICATION OF RESULTS

AT THE TOP OF THE CORE THE AXIAL PEAKING FACTOR IS APPROX 0.3. THE RADIAL PEAKING FACTOR OF THE CENTER ELEMENTS WOULD STILL BE APPROX 15. THIS GIVES A COMBINED PEAKING FACTOR OF .45. HOWEVER, THERE IS ALWAYS A SHARP UP-TURN IN THE AXIAL PEAKING FACTOR CURVE AT THE CORE-REFLECTOR INTERFACE AND IT IS NOT SAFE TO FULLY CONSIDER THE INDICATED AXIAL PEAKING FACTOR. THEREFORE, USE A COMBINED PEAKING FACTOR OF 1.0 WHICH PROVIDES FOR A FACTOR OF APPROX 2 UP-TURN IN AXIAL PEAKING FACTOR. CONSIDERING LOAD FACTOR OF 100%, THIS LEAVES AN OVERALL FACTOR OF 1.0 TO APPLY TO THE CURVE ON PAGE 15. AND THE INDICATED SHIELD THICKNESS FOR 10 MR/HR @ 3 METERS = 7.3"

CALCULATE ON-CONTACT LEVELS AND PLOT CURVE.

FOR 7.6" Pb

<u>GROUP</u>	<u>b</u>	<u>B</u>	<u>Sv</u>	<u>M_s</u>	<u>E_{FUNCTION}</u>	<u>KE</u>	<u>DOSE RATE</u>
III	13.1	4.9	2.60×10^9	.157	1.12×10^{-7}	2.1×10^{-3}	9.54
IV	10.8	4.8	3.90×10^8	.129	1.21×10^{-6}	2.6×10^{-3}	22.8
V	9.85	4.8	5.95×10^8	.118	3.23×10^{-6}	3.1×10^{-3}	121.0
VI	9.26	4.7	5.44×10^7	.110	6.17×10^{-6}	3.6×10^{-3}	25.8
TOTAL							179.1 MR/HR

REFERENCE:

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THIS RESULT INDICATES THE ON-CONTACT DOSE MAY BE LIMITING AND SHIELD THICKNESS MUST BE INCREASED. CALCULATE DOSE RATE FOR 8" Pb.

GROUP	b	B	Sv	M _s	E FUNCTION	K _E	DOSE RATE
III	13.8	5	2.60×10^9	.157	5.43×10^{-8}	2.1×10^{-3}	4.72
IV	11.4	5	3.90×10^8	.129	6.51×10^{-7}	2.6×10^{-3}	12.8
V	10.3	5	5.95×10^8	.118	2.04×10^{-6}	3.1×10^{-3}	79.7
VI	9.75	5	5.44×10^7	.110	3.65×10^{-6}	3.6×10^{-3}	16.2
TOTAL							113.4 MR/HR

THE CURVES INDICATE THAT A SHIELD OF 7 1/2" EQUIV. LEAD IS ADEQUATE IN CLOSURE HEAD TO LIMIT RADIATION LEVELS TO 10 MR/HR @ 3 METERS AND 200 MR/HR ON-CONTACT. CONSERVATIVE ASSUMPTIONS THROUGHOUT THE ANALYSIS PROVIDE ADEQUATE SAFETY MARGIN.

X BOTTOM SHIELDING

AT THE BOTTOM OF THE CORE THE AXIAL PEAKING FACTOR IS APPROX. 0.6. THE RADIAL PEAKING FACTOR IS STILL 1.5 GIVING A COMBINED FACTOR OF .90. TO ALLOW FOR SHARP UP-TURN IN AXIAL PEAKING FACTOR USE AN OVERALL PEAKING FACTOR OF 1.80 AND A LOAD FACTOR OF 100% GIVING A FACTOR OF 1.8 ON ON-CONTACT CURVE PAGE 14. INDICATED SHIELD THICKNESS IS 8.02". USE 8" EQUIVALENT LEAD IN BOTTOM.

REFERENCE:

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(REV)

XI RADIATION LEVEL AT BOLTING RING

THE SRP REPROCESSING FACILITY REQUIRES THAT PERSONNEL RECEIVE NO MORE THAN 24 MR EXPOSURE DURING CASK UNLOADING OPERATIONS. THE ONLY OPERATION IN WHICH SIGNIFICANT RADIATION EXPOSURE MAY BE ENCOUNTERED IS THE REMOVAL OF CLOSURE HEAD BOLTS AND ATTACHMENT OF CASK LIFTING LUGS. DOSE POINT IS ESTABLISHED BELOW (REF PAGE 4, 5 & 6).

ELK RIVER CASE WILL BE LIMITING SINCE PIQUA FUEL IS 12" LOWER IN BASKET THAN ELK RIVER FUEL. THIS INCREASED DISTANCE AND SLANT PATH PENETRATION THROUGH SHIELD MORE THAN OFFSETS THE SLIGHTLY HIGHER PIQUA LINE SOURCE STRENGTH (PAGE 11).

REFERENCE:

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THE DOSE RATE AT P₂ IS :

$$D_{P_2} = B_2 \frac{S_L}{2\pi a_2} F(\theta, b)$$

AT P₃ IT IS :

$$D_{P_3} = B_3 \frac{S_L}{4\pi a_3} [F(\theta_2, b) - F(\theta_1, b)]$$

$$\theta = 12.7^\circ \quad (\text{PAGE 4})$$

$$\theta_1 = \tan^{-1} \frac{11}{30} = 20.1^\circ$$

$$\theta_2 = \tan^{-1} \frac{71}{30} = 67.1^\circ$$

$$a_2 = 133''$$

$$a_3 = 30''$$

$$B_3 \approx B_2 \sec(\theta_1 + \frac{\theta_2}{4}) \text{ or } \frac{B_3}{B_2} \approx \sec 37^\circ = 1.25$$

$$\text{Then } D_{P_3} = D_{P_2} (1.25) \left(\frac{2\pi \times 133}{4\pi \times 30} \right) \left[\frac{F(\theta_2, b) - F(\theta_1, b)}{F(\theta, b)} \right]$$

EVALUATE FOR 8 3/4" LEAD SHIELD AND

$$D_{P_2} = (9.6) \left(\frac{2580}{2500} \right) = 6.35 \text{ MR/HR} \quad (\text{REF PAGE 2 \#10})$$

$$D_{P_3} = (6.35)(1.25)(2.22) \left[\frac{(3.55 \times 10^{-6}) - (2.82 \times 10^{-6})}{(2.05 \times 10^{-6})} \right] = \underline{\underline{6.3 \text{ MR/HR}}}$$

THIS ALLOWS APPROX 4 MAN-HOURS OF ACTUAL EXPOSURE TIME TO REMOVE SUPPORT BOLTS, CLOSURE NUTS AND ATTACH LIFTING LUGS. THIS IS CONSIDERED ADEQUATE FOR THIS DESIGN.

REFERENCE:

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PIQUA-ELK RIVER REACTORS SPENT FUEL SHIPPING CASK THERMAL ANALYSIS

I BASIC DATA

<u>ITEM</u>	<u>PIQUA</u>	<u>ELK RIVER</u>
REACTOR POWER - WATTS	45.5×10^6	58.2×10^6
OPERATING TIME - DAYS	515 *	640 Δ
LOAD FACTOR	100%	100% Δ
FUEL ASSY COOLING TIME - DAYS	120(MIN)	120(MIN) Δ
RADIAL PEAKING FACTOR	1.47	1.45 Δ
AXIAL PEAKING FACTOR	1.47	1.72 Δ
FUEL ASSEMBLIES PER CORE	85	148
ACTIVE LENGTH OF FUEL	54"	60" Δ
ACTIVE CORE DIAMETER	58.2"	60"
REF DWGS	7537-71801	12D02000

NOTES:

1. PIQUA DATA FROM AI SD NO. A87-710-1
AND USAEC FORM 434 DATED 7/8/60
2. ELK RIVER DATA FROM PHYSICS REPORT
DATED 5/23/60 , USAEC FORM 434
DATED 7/8/60 AND FINAL HAZARDS REPORT
DATED JULY 8 1960

* BASED ON 275 MWD/ELEMENT (HAZARDS REPORT PAGE I-3)

REFERENCE:
W-3100

PIQUA-ELK RIVER SPENT FUEL SHIPPING CASK

DRAWING NO.

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THERMAL
ANALYSIS

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II DECAY HEAT CALCULATION (REVISED)

USE DATA COMPILED IN AELE-R-3216 APPENDIX F

$$\Gamma_T + \beta (T_0 = \infty, T_s = 120 \text{ DAYS}) = 5.8 \times 10^9 \text{ MEV/SEC} \cdot \text{WATT}$$

	<u>Piqua</u>	<u>ELK RIVER</u>
$\Gamma_T + \beta(\infty, T_s)$	5.8×10^9	5.8×10^9
$\Gamma_T + \beta(\infty, T_0 + T_s)$	2.2×10^9	2.1×10^9
$\Gamma_T + \beta(T_0, T_s)$	3.6×10^9	3.7×10^9

$$Q_{\text{PIQUA}} = \frac{(3.6 \times 10^9)(45.2 \times 10^6)}{85} (1.6 \times 10^{-15})(3913) = 1050 \text{ E/HR PER AVG ASSY}$$

$$\text{"HOT-SPOT"} = \frac{1050 \cdot 147 \times 147}{54/12} = 505 \text{ BTU/HR PER FOOT}$$

$$Q_{\text{ELK RIVER}} = \frac{(3.7 \times 10^9)(58.2 \times 10^6)}{148} (1.6 \times 10^{-15})(3913) = 793 \text{ BTU/HR PER AVG ASSY}$$

$$\text{"HOT-SPOT"} = \frac{793 \times 145 \times 1.72}{60/12} = 305 \text{ BTU/HR PER FOOT}$$

CONTINUE CALCULATION BASED ON CONTINUOUS OPERATION AT FULL POWER FOR LIFE OF CORE

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III ANALYTICAL MODEL

CONSIDER A ONE-FOOT UNIT LENGTH OF CASK AND PERFORM A ONE-DIMENSIONAL ANALYSIS USING MAX HEAT RELEASE RATES PER FOOT OF FUEL ASSEMBLY. SINCE THE LOSS OF-COOLANT ACCIDENT IS THE LIMITING FACTOR IN DESIGN, PERFORM THIS ANALYSIS FIRST.

CASK CROSS-SECTION

VIQUA FUEL ASSEMBLIES WILL BE CARRIED IN ALUMINUM BASKET DIRECTLY. ROUND TO SQUARE ADAPTERS WILL BE PLACED IN BASKET TO CARRY ELK RIVER FUEL ASSEMBLIES

REFERENCE:

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IV CALCULATION OF TEMPERATURE DISTRIBUTION - PIQUA

CALCULATE T_i BASED ON FINNED SURFACE

BASIC EQUATION

$$Q = h_c A_c (T_i - T_A) + \epsilon \sigma A_R (T_i^4 - T_A^4)$$

IN WHICH

Q = TOTAL HEAT LOAD

h_c = HEAT TRANSFER COEFFICIENT

A_c = AREA EFFECTIVE FOR CONVECTION

A_R = AREA EFFECTIVE FOR RADIATION

ϵ = EFFECTIVE EMISSIVITY

σ = STEFAN-BOLTZMANN CONSTANT

T_A = AMBIENT TEMP = 100°F DESIGN

A_c = EXPOSED CASK SHELL AREA + EFFECTIVE FIN AREA

$$\text{NO OF FINS} = \frac{48\pi}{2} = 75.4 \quad \text{USE 72 FINS}$$

$$\text{SHELL AREA} = \frac{48\pi - 72(0.25)}{12} \times 1 = 11.1 \text{ FT}^2$$

$$\text{FIN AREA} = \frac{6.25(72)}{12} \times 1 = 37.5 \text{ FT}^2$$

$$\text{FIN EFFICIENCY} = \frac{\tanh(N)}{N} = \eta_F$$

JAKOB PG 235

$$N = w \sqrt{\frac{h_c}{KY}}$$

w = FIN WIDTH

h_c = HEAT TRANSFER COEFFICIENT

K = FIN THERMAL CONDUCTIVITY

Y = FIN HALF THICKNESS

REFERENCE:

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ASSUME $h_c = 0.7$ APPROX

$$N = 0.25 \sqrt{\frac{0.7}{(26)(.0104)}} = 403$$

$$\eta_f = 95\%$$

$$A_c = 11.1 + .95(375) = 46.7 \text{ FT}^2$$

$$A_R = \frac{54\pi}{12} \times 1 = 14.1 \text{ FT}^2$$

$\epsilon = 0.9$ PAINTED CARBON STEEL SURFACE

$$\begin{aligned} h_c &= 0.19(T_i - T_A)^{1/3} && \text{TURBULENT RANGE} \\ h_c &= 0.29 \left(\frac{T_i - T_A}{L} \right)^{1/3} && \text{LAMINAR RANGE} \end{aligned} \quad \left. \begin{array}{l} \\ \end{array} \right\} \begin{array}{l} \text{M. ADAMS} \\ \text{PAGE 173} \end{array}$$

EVALUATE FOR LAMINAR OR TURBULENT RANGE

$X > 10^9$ TURBULENT

$X < 10^9$ LAMINAR

$$X = L^3 \psi (T_i - T_A) \quad L = \text{FINNED SURFACE HEIGHT} \\ \text{WHICH IS APPROX } 1'$$

T_i WILL BE AT LEAST 140°F

$$X = (7)^3 (8.9 \times 10^5) (40) = 1.22 \times 10^{10} \text{ TURBULENT RANGE}$$

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CALCULATE AND PLOT CURVE OF BASIC EQUATION

For $T_i = 140^\circ\text{F}$

$$h_c = 0.19 (40)^{1/4} = 0.65$$

$$Q = (0.65)(46.7)(40) + (0.9)(14.1)(224 - 170) = 1895 \text{ BTU/HR}$$

For $T_i = 170^\circ\text{F}$

$$h_c = 0.19 (70)^{1/4} = .78$$

$$Q = (0.78)(46.7)(70) + (0.9)(14.1)(273 - 170) = 3860$$

For $T_i = 200^\circ\text{F}$

$$h_c = 0.19 (100)^{1/4} = .88$$

$$Q = (0.88)(46.7)(100) + (0.9)(14.1)(328 - 170) = 6120$$

PLOT CURVE - PAGE 7

THE HEAT LOAD ON CASK EXTERNAL SURFACE WILL BE BASED ON NINETEEN FUEL ASSEMBLIES FROM THE CENTER REGION OF THE PIQUA COKE

$$Q = (19)(1050)(1.47) = 29,200 \text{ BTU/HR}$$

• 2

THE EXTERNAL SURFACE WILL BE FINNED OVER A HEIGHT OF $6\frac{1}{2}$ FEET MINIMUM. THE INTERNAL ROCKET WILL BE 66" LONG MINIMUM. THIS MEANS THAT EFFECTIVE HEIGHT FOR HEAT DISSIPATION LIES IN BETWEEN THESE LIMITS

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PICQUA ELK RIVER SPENT FUEL CASK
OUTER SURFACE TEMP VS HEAT LOAD
AMBIENT TEMP - 100°F STILL AIR

AXIAL CONDUCTION IN THE HIGH CONDUCTIVITY ALUMINUM BASKET WILL NORMALIZE THE AXIAL PEAKING FACTOR AND AXIAL CONDUCTION IN THE LEAD WALL WILL FURTHER SPREAD THE HEAT FROM THE 66" BASKET HEIGHT. ASSUME 76" OF FIN HEIGHT IS EFFECTIVE FOR HEAT DISSIPATION

$$(WHEN \ Q \text{ PER FOOT} = \frac{29,300}{6.33} = 4630 \text{ BTU/HR})$$

FROM CURVE PAGE 7 $T_1 = 181^\circ\text{F}$

CALCULATE T_2

$$T_2 - T_1 = \frac{Q \ln(R_2/R_1)}{2\pi L K}$$

ASSUME LEAD METALLURGICALLY BONDED TO INNER AND OUTER SHELLS, NEGLECT STEEL SHELL THICKNESSES AND ASSUME WALL OF $9\frac{1}{4}"$ SOLID LEAD. FOR THIS CALCULATION THE MAXIMUM HEAT RELEASE PER FOOT OF FUEL ASSEMBLY IS USED AND NO CREDIT TAKEN FOR AXIAL CONDUCTION.

$$Q = 505 \text{ BTU/HR PER ASSY PER FOOT (PAGE 2)}$$

$$R_2 = 24"$$

$$R_1 = 14\frac{3}{4}"$$

$$K = 19$$

$$L = 1 \text{ FOOT}$$

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$$T_2 - T_1 = \frac{(19)(505)(\ln 1.63)}{2\pi(1)(19)} = 39.4^\circ\text{F}$$

USE $T_2 = 220^\circ\text{F}$

CALCULATE BASKET SURFACE TEMP - T_3

THE BASKET WILL BE DESIGNED SUCH THAT UNDER LOSS-OF-COOLANT CONDITIONS THE DIFFERENTIAL EXPANSION BETWEEN THE BASKET AND CASK WILL CLOSE THE CLEARANCE GAP BETWEEN THESE TWO PARTS AND MINIMIZE THERMAL RESISTANCE AT THIS INTERFACE. EVEN THOUGH THE BASKET WILL BE DESIGNED TO EXPAND AND CONTACT THE SHELL, ASSUME THAT ACTUAL CONTINUOUS CONTACT DOES NOT DEVELOP BECAUSE OF SURFACE IRREGULARITIES. IT IS SAFE TO ASSUME AN AVERAGE AIR GAP OF .010" EXISTS AT THE INTERFACE FOR CALCULATIONAL PURPOSES. PREVIOUS EXPERIENCE WITH THIS TYPE SYSTEM HAS SHOWN THAT THE ACTUAL LOCAL CLEARANCE VARIES FROM 0 TO .008" MAX. IN AREAS WHERE CONTACT DEVELOPS, THE IMPRINT OF THE TOOL MARKS ON THE CONTAINER SHELL HAVE BEEN OBSERVED IN THE ALUMINUM. THIS CONCLUSIVELY DEMONSTRATES THAT THIS DESIGN CONCEPT IS SOUND.

REFERENCE:

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NEGLECT RADIATION AND CALCULATE $T_3 - T_2$

$$T_3 - T_2 = \frac{Q \times X}{K A}$$

$$Q = 505 \text{ BTU/HR} \times 19 = 9600 \text{ BTU/HR-FT}$$

$$X = \frac{.010''}{12} = .00833 \text{ FT}$$

$$K = .019 \text{ @ } 250^\circ\text{F}$$

$$A = \frac{29.5 \pi}{12} \times 1 = 7.73 \text{ FT}^2$$

$$\Delta T = \frac{(9600 \times 833 \times 10^{-4})}{(.019 \times 7.73)} = 54.4^\circ\text{F}$$

$$T_2 = 275^\circ\text{F}$$

CHECK AVAILABLE THERMAL EXPANSION

$$\text{BASKET } (13 \times 10^{-6}) (29.5) (275 - 70) = .0781$$

$$\text{SHELL } (6 \times 10^{-6}) (29.5) (220 - 70) = .0266$$
$$\underline{\hspace{1cm}} .0521$$

THIS MEANS A COLD CLEARANCE OF .052" WHICH IS CLOSE BUT FEASIBLE. BASKET AND CRACK MACHINING TOLERANCES MUST BE CLOSELY CONTROLLED.

REFERENCE:

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CALCULATE T_4

CONSIDER A 60° SEGMENT OF BASKET
ONE FOOT LONG. NEGLECT AXIAL CONDUCTION

$$T_3 = 275^\circ\text{F}$$

ASSUME ALL HEAT FROM ASSY B AND $\frac{1}{6}$ OF A FLOWS
RADIALLY THROUGH A SECTION OF ALUMINUM $1\frac{1}{2}''$
THICK AND $6\frac{1}{8}''$ LONG, AND HEAT FROM ASSY'S C
AND D IS UNIFORMLY TRANSFERRED TO THIS SECTION
ALONG THE RADIUS

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$$\Delta T_{ab} = \frac{Q \times X}{KA}$$

$$\Delta T_{cd} = \frac{Q \times X}{2KA}$$

$$Q = 505 + \frac{505}{6} = 589$$

$$Q = (2)(505) = 1010$$

$$X = 0.51$$

$$X = 0.51$$

$$K = 85$$

$$K = 85$$

$$A = \frac{1.5}{12} \times 1 = 0.125$$

$$A = 0.125$$

$$\Delta T_{ab} = \frac{(589)(0.51)}{(85)(0.125)} = 28.2$$

$$\Delta T_{cd} = \frac{(1010)(0.51)}{(2)(85)(0.125)} = 24.2$$

USE COMBINED $\Delta T = 52^\circ F$ $T_4 = \underline{\underline{327^\circ F}}$

CALCULATE T_5

ASSUME $\frac{1}{6}$ OF THE HEAT FROM ASSY a FLOWS
RADIALLY THROUGH A SECTION $\frac{3}{4}$ " THICK AND
6" LONG AND ALL HEAT FROM ASSY b IS
UNIFORMLY ADDED TO THIS SECTION ALONG
RADIUS.

$$\Delta T_a = \frac{(84.2)(.5)}{(85)(.062)} = 8^\circ F \quad \Delta T_b = \frac{(505)(0.5)}{(2)(85)(.062)} = 24^\circ F$$

COMBINED $\Delta T = 32^\circ F$ $T_5 = 359^\circ F$

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CALCULATE FUEL ASSY INTERNAL TEMP

FIN DETAIL

CALCULATE T_6

ASSUME STAGNANT AIR FILM BETWEEN FUEL ASSY CAN AND BASKET .060" THICK. THIS WILL GIVE 1/8" NOMINAL CLEARANCE BETWEEN FUEL ASSY AND BASKET.

$$Q = \frac{K_a A_c (T_6 - T_s)}{x} + \epsilon' A_r \sigma (T_6^4 - T_s^4)$$

$$A_c = A_r = \frac{5.210 \pi}{12} \times 1 = 1.36 \text{ FT}^2$$

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$$E' = \frac{1}{\frac{1}{E_5} + \frac{1}{E_6} - 1}$$

SURFACE 5 IS CLEAN BRIGHT ALUMINUM - $E_5 = 0.1$

SURFACE 6 IS DARKENED SST WHICH HAS BEEN EXPOSED TO ORGANIC COOLANT AT 550 °F FOR GREATER THAN 2 YEARS - $E_6 = .55$

$$E' = \frac{1}{10 + 1.82 - 1} = .092$$

$$Q = 505 \text{ BTU/HR PER FOOT}$$

$$K = .0225 @ 400^\circ\text{F}$$

$$X = \frac{.060}{12} = .005$$

$$\text{TRY } T_6 = 440^\circ\text{F}$$

$$Q = (4.5 \times 1.36 \times 81) + (.092 \times 1.36)(1140 - 778) = 540 \text{ BTU/HR}$$

$$\text{TRY } T_6 = 435^\circ\text{F}$$

$$Q = (4.5 \times 1.36 \times 76) + (.092 \times 1.36)(1115 - 778) = 507 \text{ BTU/HR}$$

$$T_6 = \underline{\underline{435^\circ\text{F}}}$$

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CALCULATE T_7

ASSUME STAGNANT AIR CONDUCTING MEDIUM BETWEEN FINNED SURFACE AND OUTER CAN AND FIN EFFICIENCY OF 100%.

AREA EFFECTIVE FOR CONDUCTION IS A FUNCTION OF MEAN RADIUS OF FIN S.

AREA EFFECTIVE FOR RADIATION IS A FUNCTION OF FIN TIP RADIUS.

$$A_c = \frac{(2.499 \pi) 2}{12} = 1.31 \text{ FT}^2 \quad (\text{SEE PAGE 16}).$$

$$A_R = \frac{(4.910 + 2.14) \pi}{12} = 1.34 \text{ FT}^2$$

$$\epsilon' = \frac{1}{\frac{1}{\epsilon_7} + \frac{1}{\epsilon_6} - 1}$$

SURFACE 7 IS EXTRUDED ALUMINUM WHICH HAS BEEN EXPOSED TO ORGANIC COOLANT AT 550°F FOR MORE THAN 2 YEARS AND WILL HAVE A SURFACE EQUIVALENT TO OXIDIZED ALUMINUM WITH RESPECT TO EMISSIVITY. - $\epsilon_7 = 0.2$

$$\epsilon' = \frac{1}{\frac{1}{0.2} + \frac{1}{0.55} - 1} = .172$$

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DETERMINE EFFECTIVE MEAN RADIUS OF FINS
BY CALCULATING RADIUS AT WHICH FIN AREA
OUTSIDE RADIUS EQUALS ROOT AREA PLUS FIN
AREA INSIDE RADIUS.

$$.050 + 2r = 2(0.97 - r) + .010\pi$$

$$4r = .175$$

$$r = .0438$$

$$R_m = \frac{4.910}{2} + .0438 = 2.499"$$

$$\text{INSIDE CAN RADIUS} = 2.545"$$

$$\bar{X} = .096" = .008 \text{ FT}$$

$$\text{TRY } T_7 = 520^\circ\text{F} \quad K = .024 @ 475^\circ\text{F}$$

$$Q = (3)(131)(85) + (0.172)(134)(1590 - 1115) = 443 \text{ Btu/hr}$$

$$\text{TRY } T_7 = 530^\circ\text{F}$$

$$Q = (3)(131)(95) + (0.172)(134)(1660 - 1115) = 498 \text{ Btu/hr}$$

$$T_7 = 531^\circ\text{F}$$

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CALCULATE T_8

NEGLECT TEMPERATURE GRADIENT THROUGH FUEL CYLINDER AND ASSUME FINS ON INSIDE OF OUTER FUEL CYLINDER AT 531 °F. ASSUME STAGNANT AIR CONDUCTING MEDIUM BETWEEN SHELLS.

DETERMINE MEAN RADII OF FINS ON OUTSIDE OF INNER CYLINDER AND INSIDE OF OUTER CYLINDER (SEE PAGE 16)

$$R_{m7} = 2.175 - .044 = 2.131''$$

$$R_{m8} = 1.941 + .044 = 1.985''$$

$$\text{MEAN DIST } \bar{X} = .146'' = .0122 \text{ FT}$$

$$\text{MEAN } A_c = A_r = \left(\frac{4.350 + 3.882}{2} \right) \frac{\pi}{12} \times 1 = 1.08 \text{ FT}^2$$

HEAT RELEASE Q_8 IS PROPORTIONAL TO MEAN CIRCUMFERENCE OF CYLINDERS

$$\text{CIRCUM 7} = 4.630 \pi = 14.55$$

$$\text{CIRCUM 8} = 3.602 \pi = 11.32$$

$$\text{TOTAL} \quad 25.87$$

$$Q_8 = \frac{11.32}{25.87} \times 505 = 221 \text{ BTU/HIZ PER FOOT}$$

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$$T_{124} T_8 = 590^\circ\text{F} \quad K = 0.255 @ 550^\circ\text{F}$$

$$Q = (2.27)(1.08)(59) + (0.172)(1.08)(2100 - 1667) = 275^\circ\text{F}$$

$$T_8 = 590^\circ\text{F}$$

THIS IS THE MAXIMUM "HOT-SPOT" CHILLING TEMPERATURE IN DRY CASE - CASE UNFIREPROTECTED WITH DRY AIR. BECAUSE OF CONSERVATIVE ASSUMPTIONS THROUGHOUT CALCULATIONS, THIS IS AN UPPER LIMIT. SINCE CHILLING TEMPERATURE IN THE OPERATING REACTOR IS 113°F AT THE "HOT-SPOT" THE 590°F TEMPERATURE IS ALLOWABLE IN THE CASE.

V. CALCULATE TEMP. WITH ELK RIVER CASE

TOTAL HEAT LOSS IN CASE WITH ELK RIVER

$$Q = (793)(145)(19) = 21,800 \text{ BTU/HR}$$

ELK RIVER FUEL ACTIVE LENGTH IS 60", PASKET IS 66". ASSUME 76" CASE HEIGHT EFFECTIVE FOR HEAT DISSSIPATION (REF FIGURE 6,8)

$$Q \text{ PER FOOT} = \frac{21,800}{66} = 3450 \text{ BTU/HR}$$

$$\text{FROM PAGE 7 } T_1 = 166^\circ\text{F}$$

THIS INDICATES THAT IT MAY BE POSSIBLE TO SHIP ELK RIVER FUEL EARLIER THAN 120 DAYS AFTER SHUTDOWN.

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USING PREVIOUS CALCULATIONS CORRECT TEMPERATURE DISTRIBUTION FOR ELK RIVER CASE

ELK RIVER HOT-SPOT = 395 BTU/HR

PIQUET " = 505 "

} PAGE 2

$$\text{FACTOR} = \frac{395}{505} = .782$$

THIS FACTOR CAN BE APPLIED DIRECTLY TO $(T_5 - T_1)_{PIQ}$ WITH NEGLIGIBLE ERROR

$$(T_5 - T_1)_{ER} = .782 (359 - 181) = 139$$

$$T_5 = 139 + 166 = \underline{305}^{\circ}\text{F} \quad \text{MAX ALUMINUM TEMP ELK RIVER CASE}$$

ELK RIVER FUEL ASSEMBLY TEMPERATURES

Model

LET T_6 = 1ST ROW PINS

T_7 = 2ND ROW PINS

T_8 = CENTER PIN

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CALCULATE T_6

BASIC EQUATION

$$Q = h'_c A_c (T_6 - T_5) + \epsilon' A_R \sigma (T_6^4 - T_5^4)$$

$$\text{WHERE } h'_c = \left(\frac{K}{X}\right) \left(\frac{C}{L/X}\right)^{1/4} \left[\left(\frac{X^3 \rho^2 g \beta \Delta T}{\mu^2} \right) \left(\frac{C_p M}{K} \right) \right]^{1/4} \quad \text{McNOMAS PG 181}$$

$$2.1 \times 10^3 > N_{GR,x} < 2.0 \times 10^4 \quad C = 0.20 \quad N = \frac{1}{4}$$

THIS CORRELATION IS FOR VERTICAL ENCLOSED AIR SPACES WHICH IS A CONSERVATIVE WAY OF EVALUATING THIS CASE.

CHECK $N_{GR,x}$

ASSUME ΔT WILL BE ABOUT 350°F , $T_f =$
AVG $X \cong 0.7'' = .058 \text{ FT}$

$$N_{GR,x} = (.058)^3 \left(\frac{1.5 \times 10^5}{0.68} \right) (350) = 1.5 \times 10^4$$

$$h'_c = \left(\frac{.023}{.058} \right) \times \frac{0.20}{\left(\frac{5}{.058} \right)^{1/4}} \left(1.02 \times 10^4 \right)^{1/4} = .484$$

RUN TRIAL CALCULATION

$$A_c = A_R = \frac{(3.450)(4)}{12} \times 1 = 1.15 \text{ FT}^2$$

$$\epsilon' = \frac{1}{\frac{1}{\epsilon_6} + \frac{1}{\epsilon_5} - 1}$$

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$$\epsilon_6 = 0.7$$

BLACK OXIDE AFTER 2 YEARS
OPERATION IN REACTOR

$$\epsilon_5 = 0.1$$

BRIGHT ALUMINUM

$$\epsilon' = \frac{1}{\frac{1}{0.7} + \frac{1}{0.1} - 1} = .096$$

TRY $T_6 = 650^\circ\text{F}$

$$Q = (48)(1.15)(650 - 305) + (.096)(1.15)(2630 - 592)$$

$$= 190 + 225 = 415 \text{ BTU/HR}$$

TRY $T_6 = 640^\circ\text{F}$

$$Q = (48)(1.15)(640 - 305) + (.096)(1.15)(2630 - 592)$$

$$= 185 + 214 = 399 \text{ BTU/HR} \quad \text{OK}$$

THIS PRELIMINARY CALCULATION INDICATES IT WILL BE NECESSARY TO PROVIDE ADAPTERS FOR ELK RIVER FUEL ASSEMBLIES IN ORDER NOT TO EXCEED MAXIMUM ALLOWABLE CLADDING TEMPERATURES. CONSIDER ALUMINUM ADAPTER SQUARE ON INSIDE TO FIT FUEL ASSEMBLY AND ROUND ON OUTSIDE TO FIT BASKET. ALLOW FOR $\frac{1}{32}$ AIR GAP BETWEEN ADAPTER AND BASKET AND $3\frac{3}{4}$ " MAX. SQUARE INTERNAL CAVITY. DESIGNATE ADAPTER O.D. T_6 AND ADAPTER INNER SURFACE T_7 AND CALCULATE T_6 AND T_7

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$$T_6 - T_5 = \frac{Q \times x}{KA}$$

$$\Delta T = \frac{(595)(.00258)}{(.071)(158)}$$

$$\Delta T = 35.1^\circ F$$

$$T_6 = \underline{340^\circ F}$$

$$Q = 595 \text{ BTU/HR}$$

$$x = \frac{.031}{12} = .00258 \text{ FT}$$

$$K = .021 @ 725^\circ F$$

$$A = \frac{5295\pi}{12} \times 1 = 1.38 \text{ FT}^2$$

$$\text{UPPER LIMIT: } T_7 - T_6 = \frac{Q \ln \frac{r_2}{r_1}}{2\pi L K}$$

$$\Delta T = \frac{(595)(0.258)}{2\pi(1)(55)}$$

$$= .25^\circ F \text{ NEGLECT}$$

$$T_7 = \underline{340^\circ F}$$

$$Q = 595 \text{ BTU/HR}$$

$$r_2 = 2.655$$

$$r_1 = 1.875$$

$$L = 1 \text{ FOOT}$$

$$K = 55 \text{ (LOWER}$$

LIMIT CASE NO OR
DRIVING FORCE.)

CALCULATE ϵ FROM THE TEMPERATURE - T_6

ASSUME STAGNANT AIR BETWEEN PINS AND ALUMINUM.
TAKE HALF THE PIN CIRCUMFERENCE EFFECTIVE FOR
CONDUCTION AND THE PERIMETER OF THE PIN FOR
ARRAY EFFECTIVE FOR RADIATION

$$A_c = \left[12 \frac{.450}{12} \cdot \frac{\pi}{2} + 4 \left(\frac{.450}{12} \right) \frac{\pi}{4} \right] 1 \text{ FT} = 1.04 \text{ FT}^2$$

$$A_k = \left[\left(\frac{4 \times 3}{12} \right) + 4 \left(\frac{.450}{12} \right) \frac{\pi}{4} \right] 1 \text{ FT} = 1.12 \text{ FT}^2$$

WITH A_R CALCULATED IN THIS MANNER A VIEW
FACTOR OF 1.0 MAY BE USED WITH A_R

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AVERAGE DISTANCE PIN TO ADAPTERS

CONSIDER AREA WEIGHTED
AVERAGE.

$$\bar{X} = .275 - .225 \sin 45^\circ$$

$$\bar{X} = .216" = .018 \text{ FT}$$

$$\text{EFFECTIVE EMISSIVITY } \epsilon' = .096 \text{ (PAGE 21)}$$

$$K = .0235 @ 450^\circ\text{F}$$

$$Q = \left(\frac{K}{\bar{X}}\right) (A_p) (T_B - T_1) + \epsilon' \sigma A_r (T_B^4 - T_1^4)$$

$$\text{TRY } 540^\circ\text{F}$$

$$Q = (1.30)(1.04)(200) + (.096)(112)(1730 - 710) \\ = 271 + 110 = 381$$

$$\text{TRY } 545^\circ\text{F}$$

$$Q = (1.30)(1.04)(205) + (.096)(112)(1765 - 710) \\ = 278 + 114 = 392 \text{ BTU/HR OK}$$

$$T_B = \underline{545^\circ\text{F}}$$

CALCULATE 2ND ROW PIN TEMPERATURE - T_2

NEGLECT ΔT THROUGH PIN AND ASSUME 1ST ROW
INSIDE PIN SURFACE AT 545°F . BASED ON CONDUCTION
IN SST CLADDING ALONE THE UPPER LIMIT OF ERROR
FROM THIS ASSUMPTION IS APPROXIMATELY 11°F .

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FUEL ASSY INTERNAL MODEL

CONSIDER A_R FOR 2ND TO 1ST ROW PAIR OF ELEMENTS OF 2ND ROW PIN ARRAY. USE AREA AVERAGE $\bar{X}$ DISTANCE FOR CONDUCTION THROUGH TRANSPARENT AIR.

DETERMINE AVERAGE $\bar{X}$

$$\bar{X} = .750 - 2(.225 \sin 45^\circ)$$

$$\bar{X} = .432" = .036 \text{ FT}$$

HEAT TRANSFER FROM 2ND ROW TO FIRST ROW IS $\frac{9}{25} \times 395 = 142 \text{ BTU/HR}$

$$A_c = \left[4\left(\frac{450}{12}\right)\frac{\pi}{2} + 4\left(\frac{450}{12}\right)\frac{\pi}{4} \right] 1 \text{ FT} = .590 \text{ FT}^2$$

$$A_R = \left[4\left(\frac{1.5}{12}\right) + 4\left(\frac{450}{12}\right)\frac{\pi}{4} \right] 1 \text{ FT} = .618 \text{ FT}^2$$

$$\epsilon' = \frac{1}{\frac{1}{0.7} + \frac{1}{0.7} - 1} = .528$$

$$K = .026 @ 515^\circ \text{ F}$$

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TRY $T_0 = 590^\circ\text{F}$

$$Q = (0.722)(.590)(45) + .54(618)(2100 - 1765) \\ = 19 + 112 = 131 \text{ BTU/HR}$$

TRY $T_0 = 593^\circ\text{F}$

$$Q = (0.722)(593)(45) + .54(618)(2100 - 1765) \\ = 121 + 120 = 241 \text{ BTU/HR}$$

$T_0 = 593^\circ\text{F}$

CALCULATE CENTER PIN TEMP - T_{10}

$$A_c = \pi R^2 = \left(\frac{.450}{12}\right)^2 \pi = .118 \text{ FT}^2$$

$$Q = \frac{1}{25} \times 395 = 15.8 \text{ BTU/HR} \quad K = .006 \text{ in } 100^\circ\text{F}$$

TRY $T_{10} = 610^\circ\text{F}$

$$Q = (.74)(.118)(11) + .54(118)(2260 - 1765) = 10.1 \text{ BTU/HR}$$

TRY $T_{10} = 618^\circ\text{F}$

$$Q = (.74)(.118)(11) + .54(118)(2260 - 1765) = 10.5 \text{ BTU/HR}$$

$T_{10} = 618^\circ\text{F}$ MAX ALLOWED TEMP

AT HOT-SPOT IN LK4 UNIFORMIZED AIR-HEATED CASE. THIS TEMP IS ACCEPTABLE SINCE MAXIMUM CLODDING TEMP IN OPERATING CASE AT "HOT-SPOT" IS 618°F (HAZARDS REPORT PAGE II-3). SINCE THIS CALCULATION IS EXTREMELY CONSERVATIVE, ACTUAL TEMPERATURES MAY BE EXPECTED TO BE LOWER.

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THIS CONSERVATIVE ANALYSIS INDICATES THAT SHIPMENT OF FUEL ASSEMBLIES NORMALLY DRY IS POSSIBLE. IN BOTH PIQUA AND ELK RIVER CASES MAXIMUM HOT-SPOT CLADDING TEMPERATURES ARE LESS THAN MAXIMUM CLADDING TEMPERATURES IN THE OPERATING REACTOR.

Δ VI ESTABLISH BASKET DIAMETER (REF PAGE 9, 10, 19)

PREVIOUS CALCULATIONS INDICATE THAT BASKET AND SHELL TEMPERATURES IN ELK-RIVER CASE WILL BE LOWER THAN FOR PIQUA. THEREFORE, DIFFERENTIAL EXPANSION IN ELK RIVER CASE WILL BE LESS AND MUST BE USED TO ESTABLISH BASKET AND SHELL DIMENSIONS. ASSUME 30" NOMINAL DIAMETERS AND TAKE T_4 AS AVERAGE BASKET TEMPERATURE.

$$\text{BASKET } (13.5 \times 10^{-6})(30)(280-70) = 0.085 \quad \text{Alloy } 6061$$

$$\text{SHELL } (6 \times 10^{-6})(30)(196-70) = 0.023$$

$$\underline{0.062"} \quad \text{X 6}$$

THIS MEANS THAT A NOMINAL CLEARANCE OF $\frac{1}{16}"$ CAN BE ALLOWED BETWEEN BASKET AND SHELL.

FINAL DIMENSIONS

$$\text{CASK SHELL } 30.000 \pm .010$$

$$\text{BASKET OD } 29.937 \pm .005$$

IF TOLERANCES COMBINE IN WORST CASE, THE CLEARANCE CAN INCREASE .0075". THE .010" AIR GAP ASSUMED ON PAGE 9 IS ADEQUATE TO COVER THIS REMOTE POSSIBILITY.

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VII CLOSURE HEAD TEMPERATURE

WITH NO LIQUID COOLANT IN THE CASK, THE AIR IN THE SPACE BETWEEN CLOSURE HEAD AND BASKET WILL BE AT A TEMPERATURE OF SOMEWHERE BETWEEN MAXIMUM FUEL CLADDING TEMPERATURE AND MAXIMUM BASKET TEMPERATURE. THIS COULD CAUSE THE CLOSURE HEAD TO OPERATE AT A TEMPERATURE HIGHER THAN CASK WALL TEMPERATURE. PREVIOUS CALCULATIONS INDICATE FOLLOWING:

	<u>MAX CLAD</u>	<u>MAX BASKET</u>	<u>AVG</u>
Piqua	590°F	359°F	475°F
Elk River	618°F	305°F	461°F

EVEN THOUGH PREVIOUS CALCULATIONS ASSUME NATURAL CONVECTION IS SUPPRESSED, WE KNOW THAT THERE WILL BE ENOUGH CONVECTION VERTICALLY THROUGH THE FUEL ASSEMBLIES TO CAUSE THE AIR ABOVE THE BASKET TO BE HEATED. IT IS REASONABLE TO ASSUME THAT THIS AIR WILL BE AT A BULK OR AVERAGE TEMPERATURE NO HIGHER THAN THE AVERAGE AIR TEMPERATURE AT THE HOTTEST REGION IN THE BASKET AND FUEL ASSEMBLY. AS INDICATED ABOVE, THIS IS 475°F FOR ELK RIVER CASE. SINCE THIS IS BASED ON THE HOT-SPOT IN THE BASKET IT SHOULD BE CONSERVATIVE.

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IT IS NOT POSSIBLE TO DEFINE AIR VELOCITY IN THE AREA ABOVE THE BASKET DUE TO THE LACK OF KNOWLEDGE OF THE CIRCULATION PATTERN. WE DO KNOW THAT THE AIR VELOCITY WILL BE VERY LOW POSSIBLY APPROACHING A STAGNANT CONDITION. THE BEST ANALYTICAL DESCRIPTION OF THE FILM COEFFICIENT BETWEEN UNDER SIDE OF HEAD AND AIR IN SPACE BETWEEN HEAD AND BASKET IS THAT FOR HORIZONTAL PLATES FACING DOWNWARD:

$$\text{MCADAMS } h_c = 0.2 (\Delta T)^{1/4}$$

§ MARKS

HEAT TRANSFER BY RADIATION MAY BE SAFELY NEGLECTED BECAUSE OF LOW ΔT 'S AND LOW EMISSIVITY VALUES BETWEEN HEAD BASKET AND AIR.

ANALYTICAL MODEL

$$\left. \begin{aligned} Q &= (h_c + h_r)(A_1)(T_1 - T_A) \\ Q &= \frac{K}{x_m}(A_m)(T_2 - T_1) \\ Q &= h_c(A_2)(T_3 - T_2) \end{aligned} \right\} \text{SOLVE SIMULTANEOUSLY BY ITERATION}$$

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$$A_1 = 17.7 - 1.5^2 \frac{\pi}{4} = 16 \text{ FT}^2$$

$$A_2 = 2.5^2 \frac{\pi}{4} = 4.9 \text{ FT}^2$$

$$A_M = \sqrt{A_1 A_2} = 8.85 \text{ FT}^2$$

$$K = 19 \text{ (LEAD)}$$

$$X_M = 12" = 1 \text{ FOOT (SCALED FROM DWG)} \quad \frac{K}{X} = 19$$

$$\text{ASSUME } T_1 = 200^\circ\text{F} \quad h_c + h_r = 2.35$$

MARKS PAGE 377

$$Q = (2.35)(16)(100) = 3750 \text{ BTU/HR}$$

$$T_2 - T_1 = \frac{3750}{(19)(8.85)} = 22.3^\circ\text{F} \quad T_2 = 222^\circ\text{F}$$

$$h_c = 0.2(475 - 222)^{1/4} = .80$$

$$Q = (.80)(4.9)(253) = 990 \text{ BTU/HR}$$

T_1 TOO HIGH

$$\text{ASSUME } T_1 = 150^\circ\text{F} \quad h_c + h_r = 2.00$$

$$Q = (2.00)(16)(50) = 1600 \text{ BTU/HR}$$

$$T_2 - T_1 = \frac{1600}{(19)(8.85)} = 9.5^\circ\text{F} \quad T_2 = 160^\circ\text{F}$$

$$h_c = 0.2(315)^{1/4} = .84$$

$$Q = (.84)(4.9)(315) = 1295 \text{ BTU/HR}$$

$$\text{ASSUME } T_1 = 140^\circ\text{F} \quad h_c + h_r = 1.9$$

$$Q = (1.9)(16)(40) = 1215 \text{ BTU/HR}$$

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$$T_2 - T_1 = \frac{1215}{(19)(8.85)} = 7.2^\circ\text{F} \quad T_2 = 147^\circ\text{F}$$

$$h_c = 0.2 (475 - 147)^{1/4} = .85$$

$$Q = (.85)(4.9)(328) = 1365 \text{ BTU/HR}$$

CLOSE ENOUGH AGREEMENT -

USE $T_1 = 145^\circ\text{F}$, $T_2 = 153^\circ\text{F}$

AVERAGE LEAD TEMP - 150°F →

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CONSIDERATION OF SOLAR HEATING (REF MARKS 6TH ED Pg 12-114)

THE MAXIMUM SOLAR HEAT FLUX OF PRACTICAL INTEREST WILL BE IN SEPTEMBER AND IN THE AFTERNOON. THIS IS A TIME WHEN IT IS POSSIBLE TO HAVE A COMBINATION OF 100°F AMBIENT AND A HIGH SOLAR HEAT FLUX. THE SOLAR HEAT FLUX IS 3.5% GREATER IN DECEMBER BUT 100°F AMBIENT AT THAT TIME IS NOT LIKELY

SOLAR HEAT FLUX IS GIVEN BY:

$$Q = C F T A \cos \theta \text{ WHERE}$$

C = MEAN SOLAR CONSTANT - 442 BTU/FT²-HR

F = ANNUAL VARIATION - .965 IN JUNE, 1.0365 IN DEC

T = ATMOSPHERIC TRANSMITTANCE - USE 0.6

A = ABSORPTIVITY OF SURFACE - USE 0.4 (ENAMEL)
MARKS PAGE 4-109

θ = ANGLE OF INCIDENCE TO HORIZONTAL SURFACE

$$\cos \theta = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \text{ WHERE}$$

ϕ = LATITUDE - 45° N

δ = DECLINATION OF SUN - 0° SEPT 21ST

ω = HOUR ANGLE 60° FOR AFTERNOON - 4 PM

$$\text{THEN: } \cos \theta = (.707)(0) + (.707)(1)(0.5) = .303$$

$$\theta = 72.4^\circ \text{ ON HORIZONTAL SURFACE}$$

$$\text{ON VERTICAL CASK SURFACE } \theta = 90 - 72.4 = 17.6^\circ$$

$$\text{THEN } Q = (442)(1.0)(0.6)(0.4)(.95) = 101 \text{ BTU/FT}^2\text{-HR ON SOUTHWEST SIDE OF CASK.}$$

CONVERT THIS HEAT FLUX TO BTU/HR PER FOOT OF CASK HEIGHT FOR USE WITH CURVE ON PAGE 7.

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$$Q \text{ PER FOOT} = \left[\frac{48\pi \times 1}{12} \right] 101 = 12.50 \text{ BTU/HR}$$

$$Q \text{ FOR PIQUA PAGE 8} = 4630 \text{ BTU/HR}$$

$$Q \text{ SOLAR} = \frac{1250}{5880}$$

FROM CURVE PAGE 7 $T_1 = \underline{197^\circ\text{F}}$ MAX LOCAL TEMP.

NOW CONSIDER ΔT THROUGH FINS TO DETERMINE IF ACCESSIBLE SURFACES EXCEED 180°F .

FROM PAGE 6 @ 200°F HEAT DISSIPATED BY CONVECTION IS $\frac{4110}{6120} = 67\%$. OF THIS $\frac{6.25}{8.00} = 78\%$

IS DISSIPATED FROM FINS. SINCE THERE ARE 72 FINS

$$Q \text{ PER FIN} = \frac{5880}{72} (67\%)(78\%) = 42.7 \text{ BTU/HR}$$

$$\Delta T \text{ FIN (ROOT TO TIP)} \cong \frac{Q \times X}{2KA} = \frac{(42.7)(0.75)}{(-)(26)(\frac{1/4 \times 1}{12})} = 9.8^\circ\text{F}$$

FIN TIP WILL BE APPROX. 187°F WHICH IS IN EXCESS OF 180°F ALLOWABLE. THIS MEANS

THAT IF ALL CONDITIONS COMBINE TO GIVE WORST CASE, IT IS POSSIBLE THAT A LOCAL HOT-SPOT ON SOUTH FACING SIDE OF CASK COULD EXCEED 180°F . IN THIS EVENT A GUARD SCREEN OR RAIL AROUND THE CASK AT WORKING LEVEL WILL BE REQUIRED. HOWEVER, THE DECISION TO DESIGN AND FABRICATE THIS GUARD SCREEN WILL BE DEFERRED UNTIL THERMAL TEST RESULTS ARE AVAILABLE SINCE CASK PERFORMANCE WILL BE BETTER THAN CALCULATED.

REFERENCE:

DRAWING NO.

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STRESS ANALYSIS CONDITIONS

APPLYING TO CASK, LID, SUPPORT STRUCTURE
AND LIFTING FIG.

1. GENERAL DESIGN
2. SUPPORT STRUCTURE LOAD CONDITION (72.34d)
3. LIFTING LOAD CONDITION (72.34e,f)
4. STRUCTURAL INTEGRITY
AS A SIMPLE BEAM (72.32a)
5. STRUCTURAL INTEGRITY
OF CASK UNDER IMPACT (72.32b)
6. STRUCTURAL INTEGRITY
OF LID UNDER IMPACT (72.32c)
7. STRUCTURAL INTEGRITY
UNDER 100 PSI (72.32d)
8. STRUCTURAL INTEGRITY
UNDER FIRE TEST (72.34b)

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1. GENERAL DESIGN

1-1. The complete structure provides a number of features which increase the general ruggedness of design, convenience of operation, and effectiveness in the use of materials.

1. The closure head provides recessed protection for valve and rupture disc.

2. The domed shape of the head is generally "clean" in appearance and presents a faired and relatively rigid surface to external loads from all directions.

3. Lifting lugs for the head are detachable to provide this freedom from external attachment hazards under impact conditions.

4. Knuckle radii for inner and outer shells and the head reduce local stresses and vulnerability in handling and under loads.

5. Flanges and stepped joint between cask and head provide great strength and rigidity. The metal-to-metal contact between flanges provides more than usual mutual rigidity and decrease in stresses.

6. The sockets on the cask for hoisting provide a maximum of compactness and cleanliness of the outside of the cask. This concept is structurally more efficient and convenient than the conventional steel foundry schemes.

7. Support and shipping structure uses rigid members capable of resisting both tension, compression and bending stresses for economy with max. strength. These "A" frame members are designed for best performance under all conditions of loading, and are separately detachable from cask and platform for ease in handling.

8. The platform can be interchangeable in use with several casks. It can be independently (and permanently, if desired) attached to the carrier frame. Having a low profile without the A frame struts, other cargo could also use a car with such a permanent fixture.

9. Support structure design does not require additional (and relatively ineffectual) cable anchorage, but brings the entire loads of 10G laterally and fore and aft into the platform for distribution into the carrier structure.

REVISED

The presentation of material in this report follows the several conditions of loading and various design criteria described in Part 72 of the A.E.C. Regulations.

All but two require detailed calculations and are so treated in the separate parts of this stress analysis report.

The "puncture" condition is described in 72.34g. This condition is met by the use of 1" thickness (min) of steel which is acceptable for casks weighing up to 90,000# (60,000# actual).

Vibration conditions of 72.34g require that the cask shall be capable of withstanding vibration incident to shipment without impairing the integrity of the closure or of the cask itself. This condition is met because there are no elements of the cask or of the closure, and no attachments to those, which can be excited by frequencies as low as those encountered in shipment. The whole design is clean and solid, comparatively, and not subject to low frequency transportation shock excitation responses.

3/00

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1.2 PHILOSOPHY OF DESIGN

SHIPPING STRUCTURE

A The Fallacy of the Tie Rods.

The type of structure known in aircraft language as "stick and wire" is still used by riggers quite successfully. It is not uncommon to see ponderous masses "tied down" to railway cars or trucks by tension members that are incongruous. The comparative lightness of the cables is matched only by the even more questionable strength of the anchorages.

However, these installations are considered satisfactory, in spite of the very obvious lack of carry-through for the possible transportation accelerations involved. Shipping personnel estimate chances with a practiced eye, but design engineers must bring their 10G and 20G stress members right up to the division line - and dump them there.

At present, design philosophy insures that the shipping structure shall depart integrally with the cask when they both leave the car or truck platform - by accident or by intention. The actual anchorage of the structure to the car or truck is not predetermined, although this could be a matter of design and specification consistent with the rest of the assembly. As an example, the present cask is shipped in a support structure designed to transmit 300 tons in any direction horizontally. I cannot imagine that the transportation personnel will match this ability in the hold-down means to be provided.

As design items within the support structure assembly itself, tie rods operate most disadvantageously. They require duplication to secure two directional load capacity, and they only succeed in doubling the stresses over half the structural.

REFERENCE:

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B. The Value of the A-frame Struts

The A-frame is being newly discovered in architectural. A-frame shipping structure. Bracing and support assemblies have very real advantages. Primarily they provide two direction stress transmission as well as stabilizing certain load points by virtue of being a completely braced sub assembly generically.

When such high capacity structural members are provided, it is difficult to maintain the conventional direct weight supporting members in the platform without developing undesirable redundancies. This presents an opportunity for going all the way in a direction indicated by this dilemma. Let the struts support the whole weight of the cask and thereby allow reduction of the platform to a design which is not stiff in a beam sense, but deals more with the horizontal shears - from cask to platform and then to carrier floor itself.

In the present design the cask is not tied down to the platform except through the struts. Two rings at the center, one on the cask and one on the platform, engage (with vertical freedom) to transmit most of the 106 horizontal shear loads. The corner construction of the platform is essentially a pad area for welding or bolting to the carrier. Such a four point support can even allow floating the cask slightly out of vertical contact with the platform, removing beam loads from the latter and allowing it to have, in turn, only a four point contact with the carrier, instead of a continuous large area contact, subject to local and variable distortions.

This is allowable because, with a lower surface of the cask fixed against translation, the whole cask could be rigidly supported on 4 inchish, ball ended "clothespoles" or struts. Addition of any wire or other "bracing" would actually reduce the rigidity of this basic support scheme already successfully incorporated in the M-130 structural.

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2. SUPPORT STRUCTURE LOAD CONDITION (12.34 d)

This section covers the calculation of weights, the geometry of the support structure, and the stresses in that structure and certain parts of the cask immediately influenced by loads from the support structure itself. Stress limit is yield point.

2.1 WEIGHTS OF CASK, CLOSURE HEAD AND SUPPORT STRUCT.

2.1.1 SUMMARY OF WEIGHTS AND C.G.

	STEEL	LEAD	TOTALS FOR		H" TO CASK BOTTOM	M" [#] PIQUA	M" [#] ELK RIVER
			AQUA	ELK RIVER			
<u>HEAD</u>	2400	4600			99.65	239,160	
					99.87	459,400	
			7000	7000		698,560	
<u>CASK</u>	8700	37864			47.6	414,120	
			46564	46564	46.65	1,766,355	
						2,180,475	
<u>HEAD + CASK</u>	11,100	42464	53564	53564		2,879,035	2,879,035
<u>BASKET</u>			1810	1810	52	94,120	94,120
<u>FUEL ELEMENTS - PIQUA</u>		19x250	4750		52	247,000	
<u>ELK RIVER</u>		19x90		1710	52		88,920
<u>BASKET & ELEMENTS</u>			6560	3520		341,120	183,040
<u>TOTAL - CONTAINER</u>			60,124*	57,084		3,220,155	3,062,075
<u>C.G. ABOVE CASK BOTTOM</u>			53.55"	53.64"			
<u>TOTAL - SHIPPING STRUCTURE</u>			3700	3700			
<u>GROSS SHIPPING WEIGHTS</u>			63,824	60,784			

NOTE - REVISED ESTIMATES OF WEIGHTS GIVEN ABOVE
DO NOT REQUIRE REVISION OF W = 59,748* (NOW 60,124*)
IN FOLLOWING SECTION 2.2

2-1-2 CLOSURE HEAD - STEEL WT. & VOL

SECTION

		VOL. IN^3	$\times$	$H \text{ IN}$	$=$	MOMENT
a	$\frac{3}{4} (.785) (20.5)^2$	248		13.75		3420.
b	$1 \times 1 \times \pi (19.78)$	61		12.87		785.
c	$5 \times \pi (11^2 - 9.5^2) = 15.7 (121 - 90.3)$	482		11.6		5600.
d	$\frac{3}{4} \times \pi (11^2)$	286		8.50		2430.
e	$(1 \times 15) \times 2\pi / 6$	1510		11.		16,600.
f	$4\pi (24^2 - 7.3^2) = 4 (147.66)$	590		5.6		3300.
g	$1\frac{1}{8} \pi (24^2 - 15^2) = 1.175 (1102.70)$	1240		2.8		3480.
h	$3\frac{7}{8} \pi (15^2 - 13\frac{7}{8}^2) = 3.375 (123.16)$	416		1.66		690.
i	$1\frac{1}{8} \pi (13\frac{7}{8})^2 = 1.175 (583.70)$	657.		.6		396.
k	$2\frac{7}{8} \pi (27.5^2 - 24.75^2) = 2.76 (530)$	1200		2.4		2880.
PADS	$(4) (3\frac{3}{4} \times 3 \times 6)$	1010		5.3		5350.
ANGLES	$(6) (6 \times 6 \times \frac{3}{4}) \times 9\frac{1}{2}'$ 8.44"	480		8		3840.
		8180 IN^3				48,771 IN^4

C.G. AT $\frac{48,771}{8180} = 6"$

WEIGHT = $8180 \times .284 = 2323^{\#}$

ALLOW MISCL. $\frac{77^{\#}}{}$

TOTAL WEIGHT = $2400^{\#}$

REVISED

2.1.3 CLOSURE HEAD - LEAD WT. & VOL.

SECTION	VOL - IN ³	H - IN	MOMENT
a 3" FILLET $(.2146 R^3)(8 + .7766R) 2\pi$ $= .2146(9)(10.3) 6.28 =$	125.	7.8	975.
b $3\frac{3}{4}(.785)(29^2 - 27^2) = 2.94(357) =$	1050.	8.87	9320.
c $\frac{22 - 14.5}{2} (3.75) 2\pi (14.5 + \frac{7.5}{3}) =$ $3.75 (3.75) 2\pi (17) =$	1492	8.75	12300.
d $4.75 (.785) (45.5 \text{ mean})^2$	7710	4.62	35600.
e $2.75 (.785) 27.5^2$	1340	1.12	1500
	11717		59695
- ANGLES (from 2.1.2)	- 480		- 3840
	11,237 IN ³		55,859

C.G. at $\frac{55859}{11237} = 5"$

WEIGHT = $11237 \times .41 = \underline{4600}^{\#}$

REVISED

2.1.4 CASK - STEEL WT. & VOL. (DWG-F2065)

ITEM NO.		VOL-IN ³	H-IN	MOMENT
1	$84 \pi (15.68^2 - 15^2) = 84 \pi 21$	5550	57.25	284,000.
2	$1\frac{1}{4} \pi (15^2)$	885	9.75	8,640.
4	$1\frac{1}{4} \pi (24.5^2 - 15^2) = 1.25 (1178.88)$	1472	92.37	135,968.
32	$\frac{1}{2} (.785) (20^2 - 12.5^2) = .785 (\frac{1}{2}) (243.5)$	95	10.5	1,000.
5	$2\frac{3}{4} \pi (27.5^2 - 24.5^2) = 2.75 \pi (156)$	1350.	93.	125,500.
6	$92\frac{7}{8} \pi (24.5^2 - 23.5^2) = 92.62 \pi (47)$	13700	48	658,080
8	$1\frac{1}{4} \pi (23.5^2)$	2175	1.12	2440.
9	$1 \times 1\frac{3}{4} \times 124$	217.	$\frac{1}{2}$	108.
11	$1 \times (.785) 6^2$	28	$\frac{1}{2}$	14.
10	$\frac{1}{8} \times 1 \times 131$	16	$2\frac{3}{16}$	35.
20	$72 \text{ fins } \frac{1}{4} \times 3 \times 78.75 = 72 (.75) (78.75) = 4250$		46.25	196,500
21	(2) $3\frac{7}{8} \times 6\frac{1}{2} \times 9 \times (70\%)$	277	88.	24,300
23	(2) $2\frac{1}{2} \times 7\frac{1}{2} \times 7\frac{1}{2} \times (70\%)$	200	8.5	1700
		30,715 IN ³		1,438,205.

C.G. at $\frac{1438205}{30715} = 47.6"$

WEIGHT = $30,715 (284) = \underline{\underline{8700}}^{\#}$

2.1.5 CASK - LEAD WT. & VOL

sect.

	VOL-IN ³	H-IN	MOMENT
a $85.25 \pi (23.5^2 - 15.69^2)$	81,840	49.62	4,060,900.
b $.2146 (4^2) (14.6) (2\pi)$	316	7.88	2490.
c $\frac{4 \times 7}{2} 2\pi (19.5 + \frac{1}{3})$	1832	4.66	8550.
d $7 \times \frac{1}{4} (39)^2$	8362	3.5	29,200
		92350 IN ³	4,101,140

C.G. at $\frac{4,101,140}{92350} = 44.5"$

WEIGHT = $92350 \times 41 = \underline{\underline{37864}}^{\#}$

2.1.6 SHIPPING STRUCTURE - STEEL WT. (DWG 2058)

ITEM	PLATFORM	WT.
2+3	12# WF x 9'	108.#
4	$1 \times (.785) (38.875^2 - 30.575^2) (.284) = 438 (.284) =$	124.
5,6,7,8,9	28.7# L x 50'	1435.
10,11	$(4) \times 1\frac{1}{2} \times 9 \times 10 \text{ app } \times .284 = 540 \times .284$	153.
12	$(4) \times 1 \times 10 \times 14\frac{1}{2} \times .284 = 580 \times .284$	165.
13	$1 \times (.785) 12^2 \times .284 = 113 \times .284$	32.
<u>TOTAL - PLATFORM = 2017.#</u>		

STRUT ASSEMB.

		WT.#	H"	MOMENT
6	$(2) \times 12 \times 3 \times 1\frac{3}{4} \times .284 = 126 \times .284 =$	36#	90.6	3260.
5	$(2) \times 17 \times 20 \times 1\frac{1}{4} \times .284 = 850 \times .284 =$	241	84.6	20,400.
1 & 2	$(4) \left[\frac{8 \times 8 \times 3\frac{1}{2} \text{ L}}{38.9\#} \right] \times \frac{30'}{4} =$	1167	46.	53600
3	$(8) (4.5 \times 8 + 6 \times 7) \times 1 \times .284 = 624 \times .284 =$	177	8	1416
7	$(2) \left[\frac{3 \times 3 \times 7\frac{1}{2} \text{ L}}{7.2\#} \right] \times \frac{33}{12} =$	40	46	1840
<u>TOTAL 3678#</u>				80516
<u>USE 3200#</u>				

REACTION AT UPPER ATTACHMENT

$$\frac{80516}{92.5} = 870\#$$

REACTION AT LOWER END $3200 - 870 = 2330\#$

2.1.7 BASKET (PIQUA)

$$64.5 (.785) 30^2 =$$

$$-64.5 (19) (.785) 5.28^2 =$$

$$\frac{\text{Vol}}{45,592 \text{ in}^3}$$

$$-26,832$$

$$\frac{18,760 \times .097 (\text{WT OF } \#356 \text{ AL})}{= 1820\#}$$

$$-10\# \text{ CORNERS}$$

$$\underline{\text{TOTAL WT} = 1810\#}$$

REVISED

2.2

DIAGRAM OF LOADINGS

.5677 F

SIDE VIEW

END VIEW

$$L_c/b = 2.9055$$

$$L_c/2b = 1.45275$$

$$h/b = 2.5892$$

$$h/c = 1.9638$$

$$L_c/h = 1.12217$$

$$b/a = .38621$$

$$L_b/h = 1.07198$$

$$L_c/L_a = 1.06506$$

$$L_b/b = 2.7756$$

$$L_a/h = 1.0536$$

$$q/a = .33183 \quad h = \frac{a}{.33183}$$

8x8x3/4 L

$$38.24/\pi = w$$

$$11.44 = A$$

$$69.7 = I_x \approx I_y$$

$$28.2 = I_z$$

$$2.47 = r_x \approx r_y$$

$$1.57 = r_z$$

$$\frac{f}{e} = 5.0617$$

$$\frac{f}{d} = 1.0201$$

STRUT LOAD

$$= L_c = .53253 L_a$$

$$= .53253 (10536 k)$$

$$= .56107 k$$

2.2.1 GEOMETRY AND MEMBER STRESS RATIOS

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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FORE AND AFT LOADS

Hand-drawn free-body diagram of a "CASK" in "SIDE VIEW". The cask is a rectangle with dimensions 52 (width) and 92.5 (height). It is subjected to a horizontal force $F = 1000 \#$ (PILLOT LOAD) at the bottom center. The diagram shows forces on three planes: PLANE A (top), PLANE B (bottom), and PLANE C (left). On PLANE A, there is a vertical force $F_{v1} = 1778.84$ acting downwards and a horizontal force $F_{v2} = 1180.548$ acting to the right. On PLANE B, there is a horizontal force $F = 1000 \#$ acting to the right. On PLANE C, there is a horizontal force $F_{H1} = 590.274$ acting to the right and a vertical force of 1874.19 acting upwards. The right side of the cask is labeled with dimensions L_a and L_c , and a vertical force of 1874.19 acting upwards. At the bottom right corner, there is a horizontal force $F_{H2} = 590.274$ acting to the right and a vertical force of 30.695 acting upwards. A dimension a is shown at the bottom right, and a dimension 4.95 is shown near the bottom center. The text "CASK CONSIDERED SOLID" is written inside the rectangle. The caption "SIDE VIEW." is at the bottom.

 L_c $L_c = \text{STRUT LOAD}$

$$h_c = \frac{\text{STRUT}}{\text{LOAD}} = \frac{L_9}{2} \times 1.06506 = .53753 \text{ ha}$$

$$a = F_{H_2} = F_{H_1} = .33183 (1778.84)^{\#}$$

$$F_{V_1} = -F_{V_2} = \frac{92.5}{52} \times 1000^{\#} = \pm 1778.84^{\#}$$

$$L_a = 1.0536 h = 1.0536 F_v = 1874.19^*$$

$$1 \text{ STRUT LOAD} = .53753 L_9 = 998.062 \text{ \#}$$

$$\frac{\text{1 STRUT LOAD}}{F_H} = \frac{998.062}{2180.548} = .457711$$

$$F_{H_2} = F_{H_3}$$

$$\frac{F_{H2}}{F_H} = \frac{590.274}{2180.548} = .2707$$

$$\frac{F_v}{F_H} = \frac{1778.84}{2180.548} = .81577$$

$$\frac{F}{F_H} = \frac{1000}{2180.548} = .4586$$

CO-LATERAL LOADS ON STRUTS

REFERENCE:

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2.2.3 CASE 1 VERTICAL LOADING 2G DYNAMIC ↓ + 1G STATIC ↓

MAX = 3G ↓

$$V = 3G = 3 \times 60474 = 181,422^*$$

$$V/2 = 90,711^* = h$$

$$W_{\text{CONTAINER}} = 59,748^*$$

$$W_{\text{UPPER ENDS}} = \frac{726^*}{60,474^*} = 16$$

$$L_a = 1.0536 h$$

$$= 1.0536 (90,711) = 95,575$$

$$\text{1 STRUT LOAD} = .56107 h = .56107 (90,711) = -50,895^*$$

$$a \text{ for 2 STRUTS} = .33183 h = .33183 (90,711) = 30,100^*$$

2.2.4 CASE 2 FORE AND AFT LOADINGS

10G DYNAMIC ↔ + 1G STATIC ↓

$$= 597,480^* + 7260^* = 604,740^*$$

PLANE A - $\rightarrow 7260^* + .5677(597,480) = 7260 + 339,189 = 346,449$

CG - $\rightarrow (597,480 = 10G)$

PLANE B - $\rightarrow .4373(597,480) = 258,291$

FROM VERTICAL LOADINGS

$$\frac{W_1 + W_2}{2} = 30,237 = 1G \text{ AT EACH A FRAME}$$

$$L_a = \frac{95,575}{3} = 31,858$$

$$\text{1 STRUT LOAD} = -.56107 (30,237) = -16,965^*$$

$$a (2 \text{ STRUTS}) = .33183 (30,237) = 10,033^*$$

APPLIED AT
FROM HOR. LOADING - A PLANE

$$L_c = \text{1 STRUT LOAD} = .457711 (346,449) = \pm 158,574^*$$

$$a (2 \text{ STRUTS}) = .2707 (346,449) = 93,783^*$$

$$\pm h = .81577 (346,449) = \pm 282,622^*$$

TOTALS - MAX. LOAD CONDITIONS

$$\text{MAX 1 STRUT} = -16,965^* - 158,574^* = -175,539$$

$$\text{MAX } a = 10033^* + 93,783^* = 103,816$$

$$\text{MAX } h = -30,237^* \pm 282,622^* = -312,859^* a + 252,385$$

$$\text{TOTAL SHEAR AT PLANE B} = 158,881 + 258,291 = 417,172^*$$

$$\text{MAX } L_a = 1.0536 h =$$

$$329,630$$

REFERENCE:

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2.2.5 CASE 3 LATERAL LOADINGS

$$\text{COMBINED MAX - 1 STRUT} = -16,965^V - 251,653^H$$

$$= -268,618$$

MAX. SHEAR ON TOP BOLTS OF "A" FRAME

$$F_R = \sqrt{173,775^2 + 30,237^2} = 175,700$$

2.2.6

SUMMARY

	CASE 1	CASE 2	CASE 3
MAX. LOAD ON 1 STRUT	-50,895	-175,539	-268,618.
MAX "A"-FRAME LOAD (L_a) $\downarrow$	95,575	329,630	—
MAX. SHEAR TOP BOLTS IN "A" PLANE (h)	90711	-312,859* + 252,385	175,700
TOTAL SHEAR AT BOTTOM OF CASK IN "B" PLANE	—	417,172	258,291

* This assumes no support directly under cask itself.

REFERENCE:

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2.3 "A" FRAME - UPPER END AND STRUTS

2.3.1
UPPER END
"A" STRUT ASSEM.

REFERENCE:

STRESS ANALYSIS

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2.3.2 UPPER STRUT END

g - 4 HEX. HEAD BOLTS $\left\{ \begin{array}{l} \text{H.T. 150,000 PSI U.T.S.} \\ 1 \frac{1}{4} - 7 - 4 \frac{1}{4} \text{ LG.} \end{array} \right.$
 STRESS AREA = .9524 in² thru thread
 SHEAR Y.P = 95,000 PSI
 SINGLE SHEAR = 90,200 # EACH.
 TOTAL SHEAR = $4 \times 90,200 = 360,800 \text{ #}$
 OK (312,859 # MAX)

BEARING - 4 bolts in b and in c

$$S_c = \frac{312,859}{4 \times 1 \frac{1}{4} \times 1 \frac{3}{4}} = 35,700 \text{ PSI} \quad \text{OK}$$

1.5 x 30,000 Y.P. ALLOW.

JOINT BETWEEN a & b

shear of 4 bolts alone is greater than ^{shear} between b and c or between a and b.
 Note. additional weld at e and f between a and b.

f = 1" penetration weld x 14" long

e = (1" fillet weld + 1" pen. weld) x 14" long.

Total weld around block b is

$(1 + 1 + 1 \times .707) 14 = 37.9 \text{ in}^2$, giving a stress of

$$S_s = \frac{312,859}{37.9} = 8250 \text{ PSI} \quad \text{OK}$$

13,600 PSI allowable

WELD BETWEEN STRUTS AND a

29" perimeter weld and 11" filler plate weld (d) on each strut
 load is 268,618 # (tension in 1 strut and compression in adjacent strut in A frame)

Total weld = 29 + 11 = 40" of $\frac{3}{4}$ fillet weld all around.

$$\text{Stress} = \frac{268,618}{40 \times .75 \times .707} = 12,600 \text{ psi} \quad \text{OK} \quad 13,600 \text{ allowable}$$

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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2.4 "A" FRAME - LOWER END.

REFERENCE:

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2.4.2 LOWER STRUT END FITTING AND STRUT COLUMN STRENGTH

8x8x3/4 STRUT.

$$A = 11.44 \text{ in}^2$$

$$r_z = 1.57 \text{ in}$$

Equivalent length of pinned end strut

$$L' = .85(109 - 8.5 \text{ app}) = 85"$$

$$\frac{L'}{2r_z} = \frac{85}{2 \times 1.57} = 27.$$

$$\frac{P}{A} = \frac{Y.P.}{1 + \frac{eC}{r_z^2} \sec \left[\sqrt{\frac{P}{AE}} \left(\frac{L'}{2r_z} \right) \right]}$$

let $e = 1/8$ " eccentricity for mfg tolerances etc.

$$C = 3.22"$$

$$r_z = 1.57$$

$$Y.P. = 30,000 \text{ psi}$$

$$\frac{eC}{r_z^2} = \frac{(1/8)(3.22)}{1.57^2} = .1635$$

$$\frac{P}{A} = \frac{30,000}{1 + .1635 \sec \left[\sqrt{\frac{P}{A}} (27) \sqrt{\frac{1}{30 \times 10^3}} \right]}$$

$$\frac{27}{\sqrt{30 \times 10^3}} = .00493$$

$$\frac{P}{A} = \frac{30,000}{1 + .1635 \sec \left[\sqrt{\frac{P}{A}} \times .00493 \right]}$$

$$\text{let } \frac{P}{A} = 24,450 \text{ psi}$$

$$= \frac{30,000}{1 + .1635 \sec \left[\sqrt{24,450} \times .00493 \right]}$$

$$= \frac{30,000}{1 + .1635 (1.3937)} = \frac{30,000}{1.22787}$$

$$= 24,432.5 \text{ psi OK checks.}$$

$$\begin{aligned} & \sec [156.36 \times .00493] \\ &= \sec [.77085 \text{ radians}] \\ &= \sec 44.15^\circ \\ &= 1.3937 \end{aligned}$$

$$P_{allowable} = 24,450 \times 11.44 = 279,700 \text{ lb}$$

$$\text{OK } 268,618 \text{ lb design load}$$

Strut is therefore satisfactory as a column.

REFERENCE:

STRESS ANALYSIS

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$$\text{Max load} = 268,618^{\#}$$

3/4 fillet welds

$$(2 \times 4 \frac{1}{2}) + (3 \times 9) + (2 \times 1 \frac{3}{4}) = 39.5"$$

$$\text{Stress in welds} = \frac{268,618}{39.5 \times \frac{3}{4} \times .707} = 12,850 \text{ psi OK (36,000 psi allow)}$$

strut plate holes 3 1/2 and 2 1/2 dia.
Tight taper on central base plate and
mean dia. = 3 1/4" of taper

Tension area in 2 end plates 1" T-1

$$A = (6 - 3 \frac{1}{4}) \times 2 \times 1" = 5.5 \text{ in}^2$$

$$ST = \frac{268,618}{5.5} = 49,000 \text{ psi OK (100,000 Y.P.)}$$

Bearing in strut ends

$$S_b = \frac{268,618}{2 \times 3" \text{ ave}} = 44,500 \text{ psi OK (100,000 Y.P.) T-1 stock}$$

Shear Stress (P.T.B) - 3/4 OD main - 1 1/2 dia bore 150,000 PSI OTS

S_c = crushing stress in center plate (T-1 stock)

$$= \frac{268,618}{3 \frac{1}{4} \times 1 \frac{1}{2}} = 55,000 \text{ psi OK (1.5 x 100,000 Y.P. allow)}$$

$$S_b \text{ bending thru } 2 \frac{1}{2} \text{ dia} = \frac{268,618^{\#} \times \frac{1}{2} \times 1.25}{2 (2.5^4 - 1.5^4) .049} = 50,500 \text{ psi OK (135,000 Y.P. allow)}$$

$$\text{Double Shear Strength of } 2 \frac{1}{2} \times 1 \frac{1}{2} \text{ section} = \frac{268,618^{\#}}{2 (185) (2.5^2 - 1.5^2)} = 42,600 \text{ PSI OK (90,000 PSI allow shear stress)}$$

$$\text{Comb. stress} = \frac{50,500}{2} + \sqrt{25,250^2 + 42,600^2} = 74,350 \text{ psi OK (135,000 PSI Y.P.)}$$

PLATE IN BASE WELDMENT T-1 1 1/2" thick

$$\text{3/4 fillet welds} = (2 \times 10 \frac{3}{4}) + (4 \times 5 \frac{1}{4}) = 21.5 + 21 = 42.5"$$

$$S_s = \frac{268,618}{42.5 \times \frac{3}{4} \times .707} = 11,900 \text{ psi OK (19,600 PSI allow)}$$

REFERENCE:

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2.5 BOTTOM SHEAR RINGS

ON CASK AND ON BASE WELDMENT.

Design load = $417,172^{\#}$ horizontally at top of weldment

F 2055-9 Ring on cask. 1" thick $\times$ 1 1/2" wide $\times$ 39.1" D

F 2058-4 Ring on weldment 30 7/8" O.D.

Outer weld = $\pi 42 = 132"$ Due to narrow section, only a portion of this weld is assumed effective.

Section A-A can transmit in tension to opposite side of ring

only a load of $2 \times 1 \times 1.5 \times (30,000 \text{ Y.P.}) = 90,000^{\#}$

This leaves $417,172 - 90,000 = 327,172^{\#}$ to be transmitted by weld along 1/2 perimeter, with distribution assumed equal over 1/5 total circumference, as for a ball bearing.

$$\text{Load per inch of weld} = \frac{327,172}{1/5 \times 132"} = \underline{12,240^{\#}/\text{inch}}$$

Weld area per inch length is $1/4 + 1/2 + 1/2(.707) = .75 + .35 = 1.10 \text{ in}^2$

$$\text{Stress in weld} = \frac{12,240}{1.10} = \underline{11,100 \text{ PSI}} \quad \text{OK } 13,600 \text{ PSI allow.}$$

RING ON CASK.

Weld area on ring on weldment. Assume only 1/2 perimeter loaded by

load transmitted by section area, similar to above.

$$\text{Load at yield point is } 2 \times (1 \times 4) \times 30,000 \text{ PSI} = 240,000^{\#}$$

$$\text{Residual load at P is } 417,172 - 240,000 = 177,172^{\#}$$

This is developed by weld strength of area of 3/4" fillet 56" long.

$$S_s = \frac{177,172}{56 \times (.75 \times .707)} = \underline{6000 \text{ PSI}} \quad \text{OK } 13,600 \text{ PSI allow.}$$

REFERENCE:

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2-6 TIE-DOWN REQUIRED BETWEEN SHIPPING STRUCTURE AND CARRIER.

Bolting or welding anchorages are required at four corners of the support structure. Essentially the total vertical and horizontal loads are delivered to the corners, particularly the vertical tension loads. The following indicates the magnitude of an appropriate tie-down by typical bolts or else by a typical welding to the car.

Refer to pages 6 & 13. The weight (3700#) must be added to the unit weight of the complete cask, making a total of 63824#.

CASE 1 max tension load is from $2G \uparrow - 1G \downarrow = 1G \uparrow$

$$V = \frac{63824}{4} = 15,956 \# \uparrow \text{ (at each corner in every example herewith)}$$

$H = 0$
CASE 2 $10G \leftrightarrow$ plus $1G \downarrow$

$$V = \frac{282,622}{2} - 15,956 = 125,355 \#$$

$$H = 15,956 \times 10 = 159,560 \#$$

CASE 3

$$V = \frac{251,653 - 16,965}{1.12217} = 209,000 \#$$

$$H = 159,560 \#$$

Typical case of bolting assume 8 bolts 1" dia each corner

$$S_T = \frac{209,000}{8 \times .5937} = 44,100 \text{ psi}$$

Thread area = .5937
 Shank area = .785

$$S_S = \frac{159,560}{8 \times .765} = 26,100 \text{ psi}$$

$$\text{Resultant stress} = S_T = \frac{44,100}{2} + \sqrt{22,050^2 + 26,100^2} = 56,250 \text{ psi}$$

Typical case of welding

$$\text{Resultant load is } P = \sqrt{209,000^2 + 159,560^2}$$

$$\text{assume } \frac{3}{4} \text{ " fillet welds} = 262,500 \# \text{ tension}$$

$$\text{length of weld required is } \frac{262,500}{\frac{3}{4} \times 9600} = 36 \text{ " of } \frac{3}{4} \text{ " fillet weld at each corner.}$$

OK for commercial bolts as ultimate stress

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3.1 (CONTINUED)

Eccentricity of load relative to weld area pattern. Weld area (b) is on the side of the ϵ of the load opposite to that of weld areas (a, c, d). The effective eccentricity is reduced to 1."

Moment due to this eccentricity and V load is

$$M_V = 180,372 \times 1 = 180,372 \text{ in}^{\#}$$

Bending stress in socket weld metal at extreme fiber is

$$S_b = \frac{180,372 \times (3.57)}{62.07 \text{ in}^4} = 10,350 \text{ PSI}$$

Shear stress is

$$S_s = \frac{180,372}{26.22 \text{ in}^2} = 6,870 \text{ PSI}$$

Combined stress in weld at extreme fiber is

$$S_{\pi} = \frac{10,350}{2} + \sqrt{5175^2 + 6870^2} = 5175 + 8600 = 13,775 \text{ PSI}$$

This is conservative, since welding along vertical edges has been ignored, and the reinforcement in shear by the adjacent flange is also not included.

This stress is then O.K.

13,600 PSI allowable, conservatively, for welds.

I_{xx} of weld pattern

	$B \times h$	A	$Y_{\bar{00}}$	$A Y_{\bar{00}}$	$D = Y_{\bar{00}} - 5.05$	AD^2	$I_0 = \frac{B h^3}{12}$
a	.575 x 2.20	1.95	7.68	9.6	2.63	8.65	.51
b	5.25 x 1.457	7.65	9.51	72.6	4.46	152.5	1.36
c	1 x 9	9.0	5.03	45.27	0	—	60.75
d	6.5 x 1.28	8.32	.64	5.33	4.41	162.	1.14
		26.62	5.05	132.80		323.15	63.76
							386.91

Horizontal load and moment stress

$$H_1 = 101,000 \text{ #}$$

$$M = 101,000 \times 2 = 202,000 \text{ in}^{\#}$$

$$Z = \frac{386.91}{5.187} = 74.6$$

$$S_b = \frac{202,000}{74.6} = 2710 \text{ PSI}$$

$$S_s = \frac{101,000}{26.22} = 3860 \text{ PSI}$$

Combined stress is $< (2710 + 3860 = 6570 \text{ PSI})$ O.K. 13,600 PSI allow.

The welds joining the upper socket to the cask and flange are satisfactory.

REFERENCE:

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3.1 (CONTINUED)

Bearing stress of pin of hoisting gear in upper socket.

$$S_c = \frac{180,372}{4 \times 2} = 22,545 \text{ PSI} \quad \text{OK } 30,000 \text{ PSI Y.P.}$$

3.2 LOWER LIFTING SOCKET ON CASK

This is for lifting or support in the horizontal position only, and matches the pin on the dolly used in storage or transfer.

Weld Pattern - all in same plane

	$b \times h$	A	Y_{BB}	AY_{BB}	$D = Y - 4.63$	AD^2	I_o
a	1 x 2.5	2.5	5.75	13.12	.62	.96	1.3
b	2.5 x 1	2.5	7.0	52.5	2.37	42.4	.62
c	1 x 5.5	5.5	3.75	20.65	.88	4.25	13.9
d	3.5 x 1	3.5	.50	1.75	4.13	60.	.79
		19.0	4.63	88.02		107.61 + 16.11 =

2" max ecc.

$$\text{Moment} = 2 \times H_2 = 2 \times 79,372 = 158,744 \text{ inch}^2$$

$$\text{Bending stress } S_b = \frac{158,744}{26.7} = 5950 \text{ PSI}$$

$$\text{Shear stress } S_s = \frac{79,372}{19} = 4170 \text{ PSI}$$

$$\text{Combined stress} < (5950 + 4170 = 10120 \text{ PSI}) \quad \text{OK } 13,600 \text{ PSI allow.}$$

$$I = 123.72$$

$$Z = \frac{123.72}{4.63} = 26.7 \text{ min.}$$

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3.3 FLANGE LOADS

An analysis which represented the true structure and loading conditions of the two flanges would be very complex and unnecessarily time consuming. The following conditions of loading cover all the cases of this analysis and are included in this section 3.3 for convenient comparison, since only one case is determinative.

The method followed uses approximations in dealing with actual quantities, but tries to make the assumptions and the summation of stresses cover the analysis adequately.

3.3.1 Section 2 - Support Structure - gives 3 cases of loadings.

case 1 Neutral

For each A frame, h^* and a^* are given as
 $h = -90,711^{\#}$
 $a = 30,100^{\#}$ } not critical. See below.

case 3 Lateral

Flange loads are not critical, since bending moments are not a max. here.

case 2 Longitudinal is the max. stressed condition

The case is stabilized by plane S at the bottom ring contact with the base. The 10G plane is resisted here and by the two "a" components of the sloping "A" frames shown in edge view.

$$h_1 = +252,385$$

$$h_2 = -312,859$$

$$a = 103,816$$

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3.3.1 (CONTINUED)

Then the longitudinal shear (S_H) acts to rotate the cask within the flanges as shown.

$$M = 282,622 \times 52" = 14,700,000 \text{ in} \cdot \text{lb}$$

$$M = 2 \int_0^{\pi} (S_{max}) r^2 L (\sin^2 \theta d\theta) = 2 S_{max} r^2 L \int_0^{\pi} \sin^2 \theta d\theta = 2 S_{max} r^2 L \left(\frac{\theta}{2} - \frac{\sin 2\theta}{4} \right)_0^{\pi} = 2 S_{max} r^2 L \left(\frac{\pi}{2} \right) = \pi r^2 L S_{max}$$

$$\therefore S_{max} = \frac{M}{\pi r^2 L} = \frac{14,700,000}{\pi (24.5)^2 2.87} = 2710 \text{ PSI in weld.}$$

assume that only 20" of shell and weld are loaded by 'A' frame.
For steel shell 1" thick

$$M = 2 (1 \times 20 \times S_T) (24" \text{ mean radius}) = 14,700,000$$

$$S_T = \frac{14,700,000}{960} = 15,300 \text{ PSI OK } 30,000 \text{ PSI Y.P. allow.}$$

For weld

$$M = 2 (2.87 \times 20 \times S_T) (24") = 14,700,000$$

$$S_T = \frac{14,700,000}{2,760} = 5340 \text{ PSI shear in weld OK } 13,600 \text{ PSI allow.}$$

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3.3.1 (CONTINUED)

$$M_2 = (C_1) \left(\frac{13}{16} \right) = 309,359 (1.81) = 560,000 \text{ " # max at A frame.}$$

Cylindrical surfaces at (a) and (b)

$$\alpha = 12^\circ$$

$$\sin^2 \alpha = .208^2 = .043$$

$$\cos^2 \alpha = .978^2 = .958$$

Stress induced in 4 plates

$$\text{approx } \frac{M_2}{\sum Z} = \frac{560,000}{20.15} = 28,000 \text{ PSI max bending stress.}$$

This estimate is quite conservative, since no evaluation has been made of the resisting moments developed in the two flanges themselves, nor of the moments due to direct forces acting radially in (c) and (d), together with hoop stress forces in (a) and (b).

The combination of shear and such bending stresses is considered to be but little larger than the true bending stresses indicated above, and is satisfactory.

In addition to the above shear stresses in the weld and the tension in the shell, there are bending stresses in the flanges and in the plates and cylinders welded to them.

The bolts between the flanges give a mutual reinforcement which prevents a gap occurring between them.

The same angle of rotation can therefore be assumed for the two flanges and for the roots of the four plate areas in contact.

Estimate of resisting moments

Plates (c) and (d) are machined from 1 7/8 to approx 1 1/8" thickness. Assume 20" width

$$Z_{c,d} = \frac{2 (20) (1/8)^2}{6} = 8.45 \text{ in}^3$$

approximation of 20" of arcuate length.

I about a skewed axis is

$$I_{AA} = \frac{2 [bh (b^2 \sin^2 \alpha + h^2 \cos^2 \alpha)]}{12}$$

$$= \frac{2 [20 \cdot (1) (100 \cdot .043) + 1(958)]}{12} = 8.76$$

$$Z_{AA} = \frac{8.76}{1.5} = 5.85 \text{ each}$$

$$Z_{a,b} = 2 (5.85) = 11.7 \text{ in}^3$$

$$\sum Z = 8.45 + 11.7 = 20.15 \text{ in}^3$$

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3.3.2 SECTION 3

LIFTING LOAD CONDITIONS - (FLANGES)

Moment is due to weight supported by cask shell.
 $M = 159,372 \times 2.5 = 398,430$ in-lb
 Not critical.
 compared with previous case 2.

3.3.3 SECTION 6

GOG ON HD AND CONTENTS CASK.

This is uniformly distributed around flanges.
 Stress limits are low relative to ultimate stresses.

$$\frac{770,424}{\pi 52.75} = 4650 \text{ lb/linear inch}$$

$$M_1 = 4650 \times 1.875 = 8700 \text{ in-lb/linear inch}$$

Torsion bending stress =

$$S_b = \frac{M_1 R}{\sum Z} = \frac{8700 \times 24.5}{\left[\frac{3 \times 2 \times 24^2}{6} + \frac{3 \times 24^2}{6} \right]} = \frac{213,000}{4.41 + 3.79}$$

$$S_b = \frac{213,000}{8.20} = 26,000 \text{ PSI}$$

OK 30,000 psi.
 and ultimate of 70,000 CTS.
 is allowable.

The flange stresses are considered satisfactory under all conditions of analysis.

REFERENCE:

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3.4 STRESS ANALYSIS OF LIFTING RIG (F 2102)

The lifting rig is designed to lift a gross weight of 63,824[#], representing the weight of a loaded cask plus the shipping structure, with a factor of 6 on the yield stress of the materials.

$$V_{\text{each lug}} = \frac{6 \times 63824}{2} = 191,472^{\#} \quad \text{6G vertically}$$

$$H_{\text{each lug}} = 2 \times 63824 = 127,648^{\#} \quad \text{2G laterally}$$

SECTION C-C

$$I = \frac{2 [1 \times 17^3 - 1 \times 4^3]}{12} = \frac{4913 - 64}{6} = \frac{4849}{6} = 808.16 \text{ in}^4$$

$$Z_{cc} = \frac{808.16}{8.5} = 95.2$$

$$M_{ccV} = 191,472 \times 26.5 = 5,080,000 \text{ in}^{\#}$$

$$M_{ccH} = 127,648 \times 40.5 = 5,165,000 \text{ in}^{\#}$$

$$\text{Bending } S_B = \frac{5,165,000}{95.2} = 54,400 \text{ PSI} \quad \text{OK } 100,000 \text{ PSI Y.P.}$$

LIFT PIN P1

$$\text{Load} = 6 \times 63824 = 382,944^{\#}$$

$$M = \frac{382,944}{2} \times 3.75 = 718,500 \text{ in}^{\#}$$

$$Z = .098 (4)^3 = 6.28$$

$$\text{Bending } S_B = \frac{718,500}{6.28} = 114,200 \text{ PSI}$$

$$\text{Shear } S_S = \frac{382,944}{2 \times 1.785 (4)} = 15,100 \text{ PSI}$$

Combined stress is

$$S_T = \frac{114,200}{2} + \sqrt{57,100^2 + 15,100^2} = 57,100 + 59,100 = 116,200 \text{ PSI}$$

OK 150,000 PSI UTS -
125,000 PSI Y.P.

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3.4 (CONTINUED)

SECTION B-B

$$Z = \frac{2 \times 17^2}{6} = \frac{289}{3} = 96.3 \text{ in}^3$$

$$M_{BBH} = 127,648 \times 40.5 = 5,165,000 \text{ in}^{\#}$$

Stress concentration factor in bending (Roark Coe 8, pg 346)

$$r/d = 9/12 = .75 \quad h_1/h_2 = 1 \quad \therefore K = 1.22$$

Bending $S_B = \frac{M}{Z} K = \frac{5,165,000}{96.3} \times 1.22 = 65,500 \text{ PSI}$ OK 100,000 PSI Y.P.

SECTION A-A

$$Z = \frac{2 \times 12^2}{6} = 48$$

$$M_{AAV} = 191,472 \times 9.5 = 1,815,000 \text{ in}^{\#}$$

$$M_{AAH} = 127,648 \times 26 = 3,320,000 \text{ in}^{\#}$$

Bending $S_B = \frac{M}{Z} K = \frac{3,320,000}{48} \times 1.22 = 84,400 \text{ PSI}$ OK 100,000 Y.P.

Stability in this region is assured by generous curved space between the two flanges.

Tension $S_T = \frac{191,472}{2 \times 1 \times 12} = 8000 \text{ PSI}$

Combined stress = $S_B + S_T = 84,400 + 8000 = 92,400 \text{ PSI}$ OK 100,000 PSI Y.P.

Note - addition of shear stress to sections C-C and B-B not critical.

LIFT PIN P₂

$$F_{DD} = 191,472 \times \frac{9.75}{7.5} = 249,000 \text{ in}^{\#}$$

$$F_{EE} = 249,000 - 191,472 = 57,528 \text{ in}^{\#}$$

$$M_{DD} = 191,472 \times 2.25 = 431,000 \text{ in}^{\#}$$

$$Z = .098 (4)^3 = 6.28$$

Bending $S_B = \frac{431,000}{6.28} = 68,700 \text{ PSI}$

Shear $S_S = \frac{191,472}{.785 \times 4^2} = 15,200 \text{ PSI}$

Combined Stress

$$S_T = \frac{68,700}{2} + \sqrt{34350^2 + 15200^2}$$

$$= 34,350 + 37650 = 72,000 \text{ PSI}$$
 OK 150,000 UTS. 125,000 Y.P.

weld strength - principally for retaining pin

$$F = \pi (4) \cdot \frac{1}{4} (.707) 13,600 = 30,200 \text{ in}^{\#} \text{ conservative}$$

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3.4 (CONTINUED)

BLOCK D-D

2" WIDE
T-1

$$F_{DD} = 249,000 \# \downarrow$$

$$\text{Bearing on pin } S_c = \frac{249,000}{2 \times 4} = 31,125 \text{ PSI}$$

OK - 100,000 PSI
Y.P.

$$I_{\text{midsection}} = \frac{2}{12} (8^3 - 4^3) = 74.7$$

$$Z = 74.7 / 4 = 18.67$$

$$S_B = \frac{\frac{249,000}{2} \times \frac{6.5}{2}}{18.67} = \frac{405,000}{18.67} = 21,600 \text{ PSI}$$

OK - 100,000 PSI
Y.P.

Weld strength

Total weld area

$$2 (7\frac{1}{4} + 7\frac{1}{4} + 2\frac{1}{2}) \frac{3}{4} (.707) =$$

$$(17) (1.5) (.707) = 18.1 \text{ in}^2$$

$$\text{Shear } S_s = \frac{249,000}{18.1} = 13,750 \text{ PSI}$$

OK 13,600 PSI
conservative.

Note - This includes
weight of support structure.

BLOCK E-E

1" WIDE
T-1

$$F_{EE} = 57,528 \#$$

$$\text{Bearing on pin } S_c = \frac{57,528}{1 \times 4} = 14,382 \text{ PSI}$$

OK 100,000 Y.P.

$$I_{\text{midsection}} = \frac{18.67}{2} = 9.33$$

$$S_B = \frac{\frac{57,528}{2} \times \frac{6.5}{2}}{9.33} = \frac{93,600}{9.33} = 10,000 \text{ PSI}$$

OK 100,000 Y.P.

$$\text{Weld area } 2 (7\frac{1}{4} + 7\frac{1}{4} + 2) \frac{3}{4} (.707) =$$

$$16.5 (1.5) (.707) = 17.5 \text{ in}^2$$

$$\text{Shear } S_s = \frac{57,528}{17.5} = 3,280 \text{ PSI}$$

OK 13,600 PSI
allow.

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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3.5 - CLOSURE HEAD LIFTING.

DESIGN LOAD -

EACH OF 2 ATTACHMENTS IS LOADED AT 6G

$$= \frac{(6)(7000)}{2} = 21000 \# / \text{LUG.}$$

3.5.1 CLOSURE HEAD LUG.

3/4" BOLTS, SA-193 B6
 110000 PSI TENSILE
 85000 PSI Y.P.

BOLTS — TENSION

$$S_T = \frac{10500}{.334} = 31400 \text{ PSI OK } 85000 \text{ PSI Y.P.}$$

REVISED

3.5.1 (CONTINUED)

BENDING STRESS - Lug.

	AREA	d ₁	Ad ₁	d ₂	d ₂ ²	Ad ₂ ²	I _o
A	4.25	3.125	13.3	1.125	1.266	5.37	6.39
B	3	.5	1.5	1.5	2.25	6.75	.25
	7.25		14.8			12.12	6.64
						6.64	

$$\bar{y} = \frac{14.8}{7.25} = 2.04$$

$$I_{x-x} = 18.76$$

$$S_b = \frac{(21000)(4.5)}{4} \left(\frac{3.21}{18.76} \right) = 4040 \text{ PSI OK}$$

30000 PSI Y.P.

WELD. STRENGTH

$$S_t = \frac{21000}{6 (.707 \times .25 + .5)} = 5170 \text{ PSI OK}$$

13600 PSI ALLOWABLE

BEARING - 3/4" ϕ PIN IN 2 PLATES

$$S_c = \frac{21000}{(.5)(.75)(2)} = 28000 \text{ PSI OK}$$

30000 PSI Y.P.

SHEAR STRESS IN PLATE ABOVE HOLE

$$S_s = \frac{21000}{4 (1.25 \times .5)} = 8400 \text{ PSI OK}$$

18000 PSI SHEAR ALL.

TENSION IN PLATE

$$S_T = \frac{21000}{(3 - .813)(.5)(2)} = 9600 \text{ PSI OK}$$

30000 PSI Y.P.

REVISED

3.5.2 CABLE ATTACHMENT TO LIFTING RIG.

BEARING UNDER 3/4" ϕ PIN.

$$S_c = \frac{21000}{(2)(.5)(.75)} = \underline{28000 \text{ PSI}} \text{ OK}$$

30000 PSI Y.P.

SHEAR IN PLATE BELOW HOLE

$$S_s = \frac{21000}{(4)(.5)(1.25)} = \underline{8400 \text{ PSI}} \text{ OK}$$

18000 PSI SHEAR.

WELD STRENGTH -

$$S_s = \frac{21000}{(4)(3.5)(.5 \times .707 + .5)} = \underline{1755 \text{ PSI}} \text{ OK}$$

13600 PSI Allow.

REVISED

3.5.2 (CONTINUED)

BENDING STRESS IN PLATE

$$M = \frac{(21000)(4.5)}{4} = 34100 \text{ IN.LB.}$$

$$Z = \frac{(1)(3.5^3)}{6} = 2.04$$

$$S_b = \frac{34100}{2.04} = 16730 \text{ PSI OK}$$

30000 PSI Y.P.

SHEAR STRESS IN PLATE

$$S_s = \frac{\frac{21000}{2}}{(1)(3.5)} = 3000 \text{ PSI OK}$$

$$\text{TOTAL STRESS} = 16730 + 3000 = 19730 \text{ PSI OK}$$

CABLE ASSEMBLY.

CABLE IS $\frac{9}{16}$ " ϕ , 6 x 19, BREAKING STRENGTH IS 28500#

WORKING LOAD PER CABLE IS 3500# GIVING A S.F. OF $\frac{28500}{3500} \approx 8$ TO 1 MORE THAN ADEQUATE COMMERCIAL PRACTICE.

SINCE YIELD STRENGTH OF COLD DRAWN STAINLESS STEEL WIRE IN CABLE IS APPROX. 80% OF ULTIMATE, SAFETY FACTOR ON YIELD STRENGTH IS $\frac{80\% (28500)}{3500} = 6\frac{1}{2}$ TO 1

REQUIREMENT OF 72.34(f) IS MET.

THE TERMINALS WILL DEVELOP THE RATED BREAKING STRENGTH OF THE WIRE ROPE

REVISED

4. STRUCTURAL INTEGRITY AS A SIMPLE BEAM (72.32a)

$$W = 106 = 10 (60124) = 601,240 \text{ \#}$$

$$w = \frac{601,240}{92.5} = 6500 \text{ \#/inch}$$

$$M_{\max} = \frac{wL^2}{8} = \frac{601,240}{8} \times 92.5 = 6,950,000 \text{ \"#}$$

assume only outer shell is effective - very conservatively.

$$O.D. = 49 \quad I.D. = 47 \quad I = .0491 (49^4 - 47^4) = .0491 (885,120) = 43,459$$

$$Z = \frac{43,459}{24.5} = 1773.8$$

$$\text{Bending stress in shell} = M/Z = \frac{6,950,000}{1773.8} = 3920 \text{ PSI}$$

OK 33,000 PSI allow.

$$\text{max. deflection} = \frac{5}{384} \frac{wL^3}{EI}$$

$$= \frac{5}{384} \frac{(601,240) (92.5)^3}{30 \times 10^6 \times 43,459} = .0048 \text{ \"}$$

The stress limit is ultimate stresses. The design is satisfactory.

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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5. STRUCTURAL INTEGRITY OF CASK UNDER IMPACT. (72.32.6)

Design requirement - 60g load of cask on ultimate stress without deformation sufficient to cause leakage, etc.

Under impact there is a danger that the integrity of the outer shell or seals may be lost, or that the shielding function performed by the lead may be prevented due to the formation of voids by bulk displacements.

In this matter it is perhaps more important to determine strains than to consider only the calculated stresses. If shock conditions do not exceed yield stresses, then the associated strains are nominally restored by elastic behavior, so that the lead as well as the steel remain intact. If, however, a relatively small increase in stress causes permanent set, so that there is a possible shift of lead to fill this otherwise void region, then the lead so displaced must reduce the radiation protection in some other region. It is obviously better to be able to limit such stresses to the elastic range.

This leads to the recognition of two possible analytic approaches.

1) Hydrostatic pressures are developed in and by the lead, resulting from the assumed liquid flow characteristics of the lead under impact conditions. The lead cannot support itself, but must be contained by the steel structure. Here, again, we have two possible conditions of analysis.

1a) A specified kinetic energy must be absorbed, and this requires, largely, that the outer shell be stretched enough to absorb the energy as a hoop stress problem.

1b) A specified force of 60g is to be applied. This may not exceed the elastic range of stresses in the steel shell, etc., especially if reasonable allowance is made for the proven strengths of properly bonded lead to steel interfaces. This results in substantiated adherence of the lead to the steel and the impact may be successfully resisted.

2) The lead is considered well bonded to the steel and full advantage is taken of the integrity of the lead in the solid state to show that the steel structure is thereby not only protected from hydrostatic pressures, but is actually stiffened and stabilized by the lead.

REFERENCE:

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The general problem of effectively containing radiation materials within the cask under severe conditions of impact has two important areas for study:

- 1) The features of design which most seriously effect the maintaining of an impervious shell, and
- 2) The calculations of the results of imposing on the cask the various force-time-area conditions specified under 72.32.

Impact effects are difficult to estimate and costly and somewhat indeterminate in actual testing. The interpretation of test data is possibly arbitrary or inadequate, leaving much of the problem still in the realm of conjecture.

Our mathematical abilities often exceed our ability to state the physical problem clearly enough to warrant the application of complicated and sophisticated analysis. The present study has been made after a review of some such analyses, and the writer has been impressed with the need for more emphasis on both details of design and on simpler calculations of a variety of studies. The physical problems vary from surface to surface and it is considered that a proper evaluation will require multiple probes into the subject.

It is interesting to note (as one of these "probes") that the specification itself carries an implication which might be integrated into the general solution of the problem. The information contained in paragraphs 72.32 and 72.34 can be compared, and from this the conclusion made that by using steel of a certain minimum thickness, the requirements of par. 72.32 in regard to impact at 60 G could be satisfied, just as is done in par. 72.34 relative to localized or puncture force applications. For example, the present cask is of 60,000 # weight. By par. 72.34 it must withstand $30 \times 60,000\#$ for not less than 16 milliseconds over any 6" area. However, by the table, $\frac{7}{8}$ " steel is sufficient to meet this requirement.

REFERENCE:

STRESS ANALYSIS

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5.1 (CONTINUED)

In par 72:32 a force of $60 \times 60,000^{\#}$ is deemed equal to the prescribed 15 foot free fall. This is just double the force in par 72:34. Now, if reference is made to the same table, and double the weight is considered, or $120,000^{\#}$ cast weight, then $1\frac{1}{8}$ " steel is found to be a substitute for the application of such a double load value.

The conclusion is that Par 72:32, covering impact normal to any side, uses a 605 load, (or waivers for $1\frac{1}{8}$ " steel thickness) and par. 72:34, covering 6" punctured areas, uses a 305 load, or waivers for $\frac{7}{8}$ " steel thickness.

The energy absorbed by the cast from such loadings can be expressed as K.E. in foot-lbs. Since this will be converted into strain energy of the cast walls (almost entirely), it is more realistic to calculate on this basis than to contemplate the effects of 3,600,000 lbs of force and try to develop local distortion formulas.

The suggestion, therefore, is that:

- (1) Detail design configurations be made in full consideration of the awesome force of 3,600,000 lbs nominal impacting force, and
- (2) design calculations be made in regard to areas of steel which can be plastically strained to the required extent without rupture.

For Par 72:32 $P.E. = W \times 15 \text{ ft}$ ft. lbs.
 $Impulse = 60 W \times .016$ pound seconds
 $= MV$
 $\therefore V = \frac{60 W \times .016}{M} = .016 \times 60 \times 32.16 = 30.816 \text{ ft/sec}$
 $K.E. = \frac{MV^2}{2} = \frac{W}{32.16} \frac{(30.816)^2}{2} = 14.82 W \text{ ft. lbs.}$

For Par 72:34 $Impulse = 30 W \times .016$ pound seconds.
 $V = 30 \times .016 \times 32.16 = 15.435 \text{ ft/sec.}$
 $K.E. = \frac{MV^2}{2} = \frac{W}{32.16} \frac{(15.435)^2}{2} = 3.705 W \text{ ft. lbs.}$
 This is satisfied by steel $\frac{7}{8}$ " thick for $W = 60,000^{\#}$

Therefore, by appropriate proportions, Par 72:32 should be satisfied by steel $1\frac{1}{8}$ " thick.

REFERENCE:

STRESS ANALYSIS

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5.2 PLASTIC VS ELASTIC ENERGY.

The energy of the cask on drop test can be converted into

- 1) Heat
- 2) Strain energy (elastic and plastic) of the body hit.
- 3) Elastic energy of the cask
- 4) Plastic " " " "

Heat is small and negligible, and item (2) is ruled out by spec. Elastic energy is likewise small and may be neglected.

For 1 cu. in of steel at 0-30,000 psi, in the elastic range.

$$U = \frac{f^2}{2E} = \frac{30,000^2}{2 \times 30 \times 10^6} = \frac{30^2}{2 \times 30} = \underline{\underline{15}} \text{ " \# / cu in}$$

Plastic Energy

The same 1 cu in of steel may be elongated 30%, at least.

$$U = 30,000 \text{ " \#} \times .30 = \underline{\underline{9000}} \text{ " \# / cu in}$$

The estimate for plastic energy - for a given steel, at 30,000 psi Y.P. say, - depends directly on the % elongation chosen.

Hydraulic tubing (soft steel) has a specification test requiring 30% increase in inside diameter.

The area under the whole stress-strain curve for low carbon steel is reliably quoted as being 15,700 in. lbs/cu in. This takes account of a higher peak stress and maximum elongation.

Applied to the cask, it is most probable that an area of steel wall which may be expanded by hydrostatic pressure, will have a tapering pressure curve rather than a uniform pressure curve.

Therefore it is most important not to allow too great a maximum calculated elongation, since actual stress conditions might aggravate a local high stress region and produce a rupture before absorption of the total no. ft. lbs.

It is assumed here that 15% elongation is such a safe max. calculated value for expansion of cask walls and plates, and is to be combined with a conservative value of 30,000 psi.

REFERENCE:

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5.2 (CONTINUED)

Again, in reference, using 4500 $\frac{\text{in}^2}{\text{cu in}}$ as max KE value

Par 72:32 $KE = W \times 15 \times 12 = 60,000 \times 180 = 10,800,000 \frac{\text{in}^2}{\text{cu in}}$

$\frac{10,800,000}{4500} = 2400 \text{ cu in}$ of steel in the cask walls to be stressed.

Par 72:34 $KE = \frac{1}{4} \times 10,800,000 = 2,700,000 \frac{\text{in}^2}{\text{cu in}}$

$\frac{2,700,000}{4500} = 600 \text{ cu in}$ to be stressed.

This latter figure is quite revealing. For 1" steel thickness, 600 cu in corresponds to a square 24.5" on a side, presumably loaded, according to the spec., over a 6" dia. area, the whole square being plastically strained to 15% elongation. This area will actually be more extensive and have a variable stress intensity, with a peak probably in proportion to mean of $\frac{\pi}{2}$.

The problem, therefore, is to have metal in good quantity which is available for large distortion without being torn by undesirable discontinuities.

Similar conditions apply to Par 72:32, where impact is applied over a whole end or side area of the cask, or rather, an element of the cask surface on any side. Here, 2400 cu in of material must be relatively uniformly stressed.

It is considered that the conditions of par. 72:32 are most rigorous, and that those of par 72:34 will be found acceptable on examination of the results of the former loadings.

Detail analyses required for Par 72:32 will now be made.

REFERENCE:

STRESS ANALYSIS

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5.3 ROLE OF LEAD IN IMPACT CONDITIONS

Lead does not properly have a yield point, at least over long time stress applications. For impact, however, it is advisable to use the tensile stress values given in "Lead in Modern Industry."

T.S. Lead (psi)	1920	1140	710	570	280
Temp. °F	68°	180°	302°	383°	509°

At stresses below these, lead does not "flow" under sudden loadings. Consequently, to transmit pressures hydrostatically to the wall areas requires that local internal pressures be greater than those of the table above. Another authority gives chemical lead as having a yield point of 800 psi. Use 900 psi at operating temperatures.

Furthermore, lead transmits only a part of the pressure applied to it, when an axial to radial conversion is to be made.

$$q = P \left(\frac{\mu}{1-\mu} \right) = P \left(\frac{.43}{1-.43} \right) = .755 P$$

where q = lateral compressive stress

P = applied longitudinal compressive stress

(Timoshenko - Strength of Materials)
Part I - page 67

Decrease in volume of lead under uniform hydrostatic pressure.

$$\text{unit volume contraction } \Delta = -\frac{P}{K} = -P \left[\frac{3(1-2\mu)}{E} \right]$$

Assume $P = 1000$ psi

$$\Delta_{\text{lead}} = -1000 \left[\frac{3(1-2 \times .43)}{2 \times 10^6} \right] = .00021 \quad \left(\text{or } \frac{1}{50} \text{ of 1 percent} \right)$$

Negligible

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5.4

CRITICAL EXTERNAL PRESSURE.

Collapse of the lower portion of the inner shell under impact can occur just below the yield point of the clad steel. Pressure p' is assumed transmitted equally to the side and the end of the vessel by the lead, acting as a hydraulic fluid at pressures greater than 800 psi, the minimum value for yield point of chemical lead.

Roark, Case R, Table XVI, page 318 covers a thin tube with closed ends under uniform external pressure, lateral and longitudinal.

$l = 9.5''$, overall, to bottom of support provided by aluminum basket

$R = 15.5''$ outside

$r_s = .75''$ for clad shell

$$p' = \frac{E \left(\frac{r}{R} \right)}{1 + \frac{1}{2} \left(\frac{\pi R}{m l} \right)^2} \left\{ \frac{1}{m^2 \left[1 + \left(\frac{m l}{\pi R} \right)^2 \right]^2} + \frac{m^2 r^2}{12 R^2 (1 - \nu^2)} \left[1 + \left(\frac{\pi R}{m l} \right)^2 \right]^2 \right\}$$

where m = no. lobes formed in buckling

$$\frac{r}{R} = .0484 \quad \frac{l}{R} = \frac{9.5}{15.5} = .61 \quad \pi R = 48.7 \quad \frac{1}{2} \left(\frac{\pi R}{l} \right)^2 = 13.2 \quad \frac{r^2}{12 R^2 (1 - \nu^2)} = 2.14 \times 10^{-4}$$

$$\therefore p' = \frac{30 \times 10^6 \times .0484}{1 + \frac{13.2}{m^2}} \left\{ \frac{1}{m^2 \left[1 + \frac{m^2}{26.4} \right]^2} + m^2 \times 2.14 \times 10^{-4} \left[1 + \frac{26.4}{m^2} \right]^2 \right\}$$

$$\text{for } m=1 \quad p' = \frac{1.44 \times 10^6}{14.2} \left\{ \frac{1}{1.075} + 2.14 \times 10^{-4} [27.4]^2 \right\} \\ = 101,000 \{ .93 + .16 \} = 101,000 (1.09) = \underline{110,000 \text{ psi}}$$

$$\text{for } m=3 \quad p' = \frac{1.44 \times 10^6}{2.47} \left\{ \frac{1}{9 \times 1.8} + 19.26 \times 10^{-4} [15.5]^2 \right\} \\ = 582,000 \{ .0616 + .03 \} = 582,000 \times .0916 = \underline{53,400 \text{ psi}}$$

$$\text{for } m=10 \quad p' = \frac{1.44 \times 10^6}{1.132} \left\{ \frac{1}{2300} + 214 \times 10^{-4} (1.6) \right\} = 1.27 \times 10^6 \times .0247 = \underline{31,300 \text{ psi}}$$

REFERENCE:

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5.4 (CONTINUED)

$$\text{for } m=4$$

$$P' = \frac{1.44 \times 10^6}{1.825} \left\{ \frac{1}{16(1.605)^2} + 16 \times 2.14 \times 10^{-4} [2.65]^2 \right\}$$

$$= 790,000 \{ .0242 + .0239 \} = 790,000 \times .0481 = 38,000 \text{ psi}$$

$$\text{for } m=5$$

$$P' = \frac{1.44 \times 10^6}{1.528} \left\{ \frac{1}{25(1.95)^2} + 25 \times 2.14 \times 10^{-4} (2.05)^2 \right\}$$

$$= 943,000 \{ .0105 + .0224 \} = 943,000 \times .0329 = 31,000 \text{ psi}$$

$$\text{for } m=6$$

$$P' = \frac{1.44 \times 10^6}{1.367} \left\{ \frac{1}{36(2.36)^2} + 36 \times 2.14 \times 10^{-4} [1.732]^2 \right\}$$

$$= 1,052,000 \{ .005 + .0231 \} = 1,052,000 \times .0281 = \underline{\underline{29,600 \text{ psi}}}$$

$$\text{for } m=7$$

$$P' = \frac{1.44 \times 10^6}{1.27} \left\{ \frac{1}{49(2.85)^2} + 49 \times 2.14 \times 10^{-4} (1.5)^2 \right\}$$

$$= 1,135,000 \{ .0025 + .0250 \} = 1,135,000 \times .0275 = 31,200 \text{ psi}$$

therefore, a pressure of 29,600 psi is required to buckle the side wall, and failure would be in a 6 lobe pattern.

Further investigation shows the influence of (τ) on (P') .

again, for $m=6$ let τ be reduced to $\frac{3}{8}$ ", or half the original value.

$$P' = \frac{1,052,000}{2} \left\{ .005 + \frac{1}{4} (.0231) \right\} = 526,000 (.0108) = \underline{\underline{5700 \text{ psi}}}$$

$$\text{For } m=7$$

$$P' = \frac{1,135,000}{2} (.0025 + \frac{.025}{4}) = 567,500 (.00875) = \underline{\underline{4900 \text{ psi}}}$$

$$\text{For } m=10$$

$$P' = \frac{1,270,000}{2} (.000435 + \frac{.0243}{4}) = 635,000 (.0065) = \underline{\underline{4130 \text{ psi}}}$$

$$\text{For } m=20$$

$$P' = \frac{720,000}{1.0325} \left\{ \frac{1}{400(16.5)^2} + 400 \times 2.14 \times 10^{-4} [1.066]^2 \right\}$$

$$= \frac{696,000}{2} (.0000092 + \frac{.097}{4}) = \frac{696,000}{2} (.02425) = \underline{\underline{8430 \text{ psi}}}$$

REFERENCE:

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5.4 (CONTINUED)

Even with the cylinder wall below the basket reduced to $\frac{3}{8}$ thickness, a pressure of about 4000 psi would be required for unstable collapse. The hoop stress - compressive - would be

$$S_c = \frac{4000 R}{t} = \frac{4000 \times 15.5}{\frac{3}{8}} = 165,000 \text{ psi} \quad \text{Excessive}$$

The opportunity is thus available for some energy absorption by external pressure while keeping the circular configuration stabilized.

Plastic flow can be assumed to start at approx 30,000 psi min. y.p. This corresponds to an external pressure from the load of

$$P = \frac{30,000 t}{R} = \frac{30,000 \times \frac{3}{8}}{15.5} = \underline{730 \text{ psi}}$$

Assume $t = \frac{1}{2}$ " For a yield point of 30,000 psi the external pressure

is $P = \frac{30,000 \times \frac{1}{2}}{15.5} = \underline{970 \text{ psi}}$ This means that plastic flow in the cylinder wall would start at, or slightly after, the load is assumed to become plastic (at 800 psi for chemical load to about 1180 psi for commercial load).

The approximate pressure required to collapse the cylindrical configuration would be

For $m = 10$

$$\begin{aligned} P' &= \frac{30 \times 10^6 \frac{1}{2}}{15.5} \left\{ \frac{1}{10^2 \left[1 + \frac{10^2}{26.4} \right]^2} + \frac{10^2 \times (\frac{1}{2})^2}{12 \times 15.5^2 (91)} \left[1 + \frac{26.4}{10^2} \right]^2 \right\} \\ &= \frac{968,000}{1.132} \left\{ \frac{1}{100 (4.8)^2} + 0.0955 [1.264]^2 \right\} = 852,000 \left\{ \frac{1}{2300} + 0.152 \right\} \\ &= 852,000 (0.156) = \underline{133,000 \text{ psi}} \end{aligned}$$

The range of hydrostatic pressures between, say, 800 psi and 13,000 psi, is therefore potentially available for general application to the problem of energy absorption under shock loadings. This is tentative and subject to examination of all other areas to be stressed in the plastic state.

REFERENCE:

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5.5 ENERGY ABSORBED BY LOWER SHELL

assume $\chi = -1/2$, contraction on 15.5" radius.

Section area of shell wall = $9.5 \times 1/2 = 4.75 \text{ in}^2$

mean contraction assumed $2/3 \times 1/2 = 1/3$

mean shortening of wall periphery = $\frac{2\pi}{3} = 2.09$

hoop force = $4.75 \text{ in}^2 \times 30,000 \text{ psi} = 142,500 \text{ lbs}$

Energy required to compress cylindrical ring radially inward is approximately $U = 142,500 \text{ lbs} \times 2.09 \text{ in} = 300,000 \text{ in-lbs}$, in the plastic range, for an implosion distance corresponding to $\chi = 1/2$, as above.

This is but a small part (about $1/36$) of energy to be absorbed. Therefore, this side wall of the inner cylinder is too small in its contribution to energy absorption to really count.

In fact such a small inward deflection would not be destructive, but would undoubtedly "freeze" the basket in the cork.

REFERENCE:

STRESS ANALYSIS

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5.6 IMPACT OF CASK ON ITS BOTTOM SURFACE

Distribution of 60W loads

$$\begin{aligned}
 \text{Head } 60 \times 6344 &= 380,640 \text{ " total} \\
 \text{Cask } 60 \times 8350 &= 498,000 \text{ " steel} \\
 &60 \times 38,544 = 2,312,640 \text{ " lead} \\
 \text{Bottom } 60 \times 6560 &= 393,600 \text{ "} \\
 &\underline{3,584,880 \text{ "}}
 \end{aligned}$$

Compressive stress in outer cylinder at level A due to steel and lid.

$$\begin{aligned}
 &\frac{380,640 + 393,600 + 498,000}{1,272,240 \text{ "}} = \frac{1,272,240}{\frac{\pi}{4}(48^2 - 46.5^2)} = \frac{1,272,240}{\frac{1885}{187} \text{ in}^2} = \underline{6810 \text{ psi compressive}}
 \end{aligned}$$

Pressure of lead on bottom plate at level A (assumed hydrostatic)

$$\frac{2,312,640}{1698} = \underline{1365 \text{ psi}} \text{ at "head" of 92" axial}$$

$$.755 \times 1365 = \underline{1025 \text{ psi radial}}$$

Hoop stress in cylinder = $\frac{1025 \times 47}{2 \times 1} = 24,100 \text{ psi}$ just above plane A.

$$f_{\text{hoop}} = \frac{P d}{2 t_s} = \frac{1025 \times 46.5}{2 \times 1.4} = 19,000 \text{ psi at level A} \leftarrow \text{still in elastic range.}$$

K.E. in cylinder

Average hoop stress over 92" length is 9500 psi

$$\Delta E = \frac{9500}{30 \times 10^6} = 316.6 \times 10^{-6}$$

$$\text{Perimeter (mean)} = \pi \times 48 = 150.80$$

$$\text{Elongation of circumference} = 316.6 \times 150.8 \times 10^{-6} = 0.047700 \text{ "}$$

$$\text{Tension across section} = 92 \times 9500 \times 1 = 874,000 \text{ " #}$$

$$\text{KE} = 874,000 \times 0.0477 = \underline{41,700 \text{ " #}} \text{ at } 19,000 \text{ psi hoop stress}$$

Just above the knuckle (8" up)

wall is 1" thick and hoop stress is $+24,100 \text{ psi}$

assume compressive stress is still $= -6810 \text{ psi}$

$$\text{app } \underline{25,010 \text{ psi}} \text{ approx elastic.}$$

REFERENCE:

STRESS ANALYSIS

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5.6 (CONTINUED)

So far this condition represents the immovable object and the irresistible force. The flat plane it hits is specified as "unyielding". The steel in the cask is so far all below the yield point. Yet there is 3.6M force and 10.8M inch lbs of energy unaccounted for.

A concrete abutment would partly crumble.

Here, by decree, the cask must yield.

Therefore, let us take another look at the exact terms imposed.

1) By stating that 60 W is the load, no matter how long it may be applied, is to say that if the cask has sustained this load without passing the yield point, as shown above, it is safe. There will be no further change of state, regardless of the time. This is approach 1-B.

By this interpretation the cask is A.O.K.

Now consider approach 1-a.

2) Note, however, that the condition that it be a free fall impact has quite a different physical interpretation. In this case the energy will not be refused its necessary absorption by such parts of the cask as will yield. The phenomenon does not limit the stress developed, thus making it a truly irresistible force mashing the cask against an immovable flat surface.

Let us now study this more severe interpretation.

First note that the inner shell is buoyant in the lead. The combined weight of head and shell and contents is

$$\begin{array}{r} 380,640 \\ 393,600 \\ \hline 774,240 \text{ #} \end{array}$$

This is bolted to the outer shell, but the lead in the head and the basket etc are somewhat elastically supported on the lower plate of the head and on the upper annulus at the top of the cask proper. At most, this total weight, if distributed over only the 31" dia of the bottom of the inner shell, would give

$$\frac{774,240}{\pi/4 \cdot 31^2} = \frac{774,240}{755} = 1025 \text{ psi} \downarrow \text{ This is less than}$$

$$1365 \times \frac{85}{92} = 1290 \text{ psi} \uparrow \text{ hydrostatic pressure upward from the lead.}$$

REFERENCE:

STRESS ANALYSIS

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5.6 (CONTINUED)

Second, note that the steel shell will yield in the plastic state enough to absorb the required kinetic energy. This radial bulging will occur below the level at which stresses from whatever cause exceed the nominal yield stress of 30,000 PSI. This may be increased, as a minimum, if the steel lot has an actual yield stress of greater value. The problem, then, is to make it physically possible, by "smooth" design without exaggerated stress raisers, to relatively uniformly stretch the outer shell at stresses between, say 30,000 to 50,000 PSI.

To absorb 10,800,000 " # kinetic energy in bottom impact, the stress plot will be approximately as shown.

$$\text{Mean stress} = 40,000 \text{ PSI}$$

$$\text{Hoop force} = 36.8 \times (1 \text{ thickness}) \times 40,000 \text{ PSI} = 1,472,000 \text{ #}$$

$$\text{Elong. required} = \frac{10,800,000 \text{ #}}{1,472,000 \text{ #}} = 7.32 \text{ (} \approx 2.33 \text{ diam increase)}$$

$$\text{Radial pressure (max)} =$$

$$\frac{2 \times 50,000 \times 1}{47 \text{ dia}} = 2175 \text{ PSI}$$

$$\text{axial pressure is therefore}$$

$$\frac{2175}{.755} = 2820 \text{ PSI required to produce this shell dilation.}$$

By previous calculations, 1365 PSI resulted from 60 G loading.

Therefore, in free fall, approx $\frac{2820}{1365} \times 60G = 124G$ would be indicated.

SHIELDING LOSS &

VOLUME INCREASE

The 8" lead thickness, 36.8" long, with average extension circumferentially of 7.32", will increase in volume

$$\Delta V = 36.8 \times 8 \times 7.32 = 2160 \text{ in}^3$$

This must also represent a decrease in the thickness of the lead shield over the base of the cask.

$$\Delta t = \frac{2160 \text{ in}^3}{785 (4 \pi)} = 1.25 \text{ " decrease}$$

This is allowable, since a limit of 2" loss of shielding is specified.

REFERENCE:

STRESS ANALYSIS

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5-7 IMPACT OF CASK ON ITS SIDE.

This case presents two different conditions.
 at A the section is that of a deep ring, absorbing energy by plastic distortion radially.
 at B the shell will tend to flatten and then build up resistance by internal hydrostatic pressure of the load, eventually stretching the shell.

This expansion area, which we count on to absorb substantially all the K.E. of the fall, will be located both near the surface struck, where the internal pressure is greatest, and outward of the shell area flattened by contact with this impact surface. The resulting section will resemble that of a water drop on a plane surface, as shown on following page.

For section A

CG of section A	y	Ay
$(3.5 \times 2) = 7.0$	$7.0 \times 1 = 7.0$	
$(2.5 \times 2.5) = 6.25$	$6.25 \times 1.75 = 10.94$	
$(10.5 \times 1/8) = 1.31$	$1.31 \times 7.75 = 10.15$	
$(8.5 \times 1/8) = 1.06$	$1.06 \times 6.75 = 7.16$	
	<u>34.63</u>	<u>165.02</u>

$$Y = 4.75$$

$$\frac{R}{C} = \frac{21.25}{7.75} = 2.75$$

$$I = \frac{6.0 \times 4.75^3}{3} - \frac{2.38 \times 2.75^3}{3} - \frac{1.38 \times 2.25^3}{3} + \frac{1/8 \times 7.75^3}{3} + \frac{1/8 \times 6.25^3}{3}$$

$$= 214.2 - 16.45 - 5.23 + 175.4 + 91.5 = 459.$$

$$C = 7.75 \quad \text{for } R/C = 2.75 \quad K = \text{app } 1.4 \text{ in } S = K \frac{Mc}{I} \quad (\text{Sally})$$

Roark VIII-1

$$M = .3183 WR = .3183 \left(\frac{60}{2} \times 59,748 \right) 21.25 = 12,100,000 \text{ " #}$$

$$S_b = \frac{12,100,000 \times 1.4 \times 7.75}{459} = 286,000 \text{ psi for 30G without assist. and with 2 point loading.}$$

Obviously, with this stiff ring overstressed to this extent, reliance must be placed on action of contents in supporting extreme loadings, and on providing energy absorption in a manner related to the foregoing cases.

For section B

Assume that the action will be substantially as drawn in the following diagram, showing a flattened area of impact and bulges at the sides which have been both distorted by the contact and expanded locally by the hydrostatic pressure, which has a "head" of 42" at the flattened wall level.

REFERENCE:

STRESS ANALYSIS

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5.7 (CONTINUED)

Contact is made first on the fins, and after crushing these, the load transfers to the end plate and the head flanges.

A logical pattern of deformation is shown. Approximately a 5" indentation is possible and probable as a maximum, if the hydrostatic analysis is accomplished in actual performance.

of 50,000 PSI is assumed as max pressure,

$$\text{Elongation of shell} = \frac{10,800,000 \text{ in}^2}{\left(\frac{50,000 + 30,000}{2}\right) (94 \text{ in} \times 1 \text{ in thick})} = 2.88 \text{ in} \text{ net elongation of shell over semi-circumference.}$$

This corresponds to a volume increase found as follows: -

$$\pi R_2 = \pi R_1 + 2.88 \text{ equating circumferences of half shell conditions}$$

$$R_2 = R_1 + .915$$

$$\frac{\pi R_2^2}{2} = \frac{\pi (R_1 + .915)^2}{2} = \frac{\pi R_1^2}{2} + A_{\text{increase}}$$

$$R_1^2 + 1.83 R_1 + .839 = R_1^2 + \frac{2A}{\pi} \quad R_1 = 24$$

$$A = \frac{\pi}{2} [(1.83 \times 24) + .839] = \frac{\pi}{2} (44.839) = 70.7 \text{ in}^2 \text{ increase in section}$$

allowing for a tapered deformation over 60" length, the volume increase could be $\frac{70.7 \times 60}{2} = 2121 \text{ in}^3$

c.f. 2160 in³ for bottom impact.

The loss of shielding would be > 2" over an arc of approx 60°.

However, this flattened area would be against the contacting mass, if dropped, and may be assumed to be without hazard until removed under protected conditions.

In the light of recent drop tests, the above figures seem unnecessarily severe.

The construction is therefore presumed to be satisfactory in this impact condition.

REFERENCE:

STRESS ANALYSIS

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5.8 ELLIPSE & CIRCLE OF SAME AREA

Since the circle has a minimum circumference for its area, any change in shape involves an increase in peripheral length. Therefore, a cylindrical shell, filled with lead, and both flattened and distorted by external pressure, will be elongated as well as locally bent to a different radius. The energy absorbed in bending the thin shell will be neglected, it being much more important to estimate the % of stretch involved.

For example assume a 10% decrease in a diameter of a circle by loading between two planes in transverse compression.

$$\text{area} = \pi a b \text{ where } b = .90r$$

$$= \pi r^2 \text{ of circle}$$

assume the areas are equal.

$$\therefore a = \frac{r^2}{b} = \frac{r^2}{.90r} = \frac{r}{.90} = 1.111r$$

$$\frac{a}{b} = \frac{r}{.90} \times \frac{1}{.90r} = \frac{1}{.81} \therefore b = .81a$$

Perimeter

$$S = \pi(a+b) \left[1 + \frac{1}{4} \left(\frac{a-b}{a+b} \right)^2 + \frac{1}{64} \left(\frac{a-b}{a+b} \right)^4 + \frac{1}{256} \left(\frac{a-b}{a+b} \right)^6 + \dots \right]$$

for $b = .81a$ as above

$$S = \pi(1.81a) \left[1 + \frac{1}{4} \left(\frac{.19a}{1.81a} \right)^2 + \frac{1}{64} (.104972)^4 + \frac{1}{256} (.104972)^6 + \dots \right]$$

$$= 5.68628876a \left[\begin{array}{r} 1.00000000 \\ .00275478 \\ .00000190 \\ .00000000 \\ \hline 1.00275668 \end{array} \right]$$

$$= 5.7019252a$$

$$\text{For a circle } S = 2\pi(r) = 2\pi(.90a) = 5.6548728a$$

$$\therefore \frac{\Delta S}{S} = \frac{.0470524}{5.6548728} = .00832$$

In the present case, this 10% diametral flattening gives $\Delta S = .00832 \times \pi \times 48 = 1.2546$

The corresponding energy to elongate a section of shell 1" thick & 1" length (area)

$$Q = (30,000 \text{ psi} \times 1 \times 1) \times 1.2546 = 37,638 \text{ in lbs per inch length shell}$$

For 92" of lead length of shell, total energy of this expansion is

$$92 \times 37,638 \text{ in lbs} = 3,460,000 \text{ in lbs}$$

$$\text{Required energy} = 10,800,000 \text{ in lbs for spec 72:32}$$

Note that the above 3,460,000 in lbs represents an expansion of only .832%
Proportionately, shell 10,800,000 in lbs would be absorbed by 2.6% expansion

REFERENCE:

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5.8 (CONTINUED)

ESTIMATED DISTORTION OF CYLINDER
DUE TO IMPACT ON PLANE SURFACE.

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REFERENCE:	STRESS ANALYSIS		DRAWING NO.
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G. STRUCTURAL INTEGRITY OF LID UNDER IMPACT (72.32C)

assume total impact on head is taken, conservatively, on the 6 angles.

$$S_c = \frac{3,607,440}{.866 \times 79.38} = 52,500 \text{ PSI} \quad \text{OK. } 60,000 \text{ PSI ultimate for short columns.}$$

By this means the entire shock load is transmitted directly to the cask, and loss of shielding by displacement of the lead is prevented. Any yielding of the bottom plate would not cause noticeable axial displacement of lead.

Welding stresses

area of weld at bottom end of 6 struts

$$A = 6 \times 38 \times \left(\frac{1}{2} \times .707\right) = 80.5 \text{ in}^2$$

$$S_c = \frac{3,607,440}{.866 \times 80.5} = 51,800 \text{ PSI}$$

OK. Air Force std max. ult. allowable weld stress is 51,000 PSI

This is conservative and neglects entirely the load capacity of the flanged and dished head, and also that of the lead bonded to all surfaces.

G.1 IMPACT AGAINST SIDE EDGE OF HEAD.

15x wt. of loaded cask is $F = 15 \times 60,124 = 901,860^*$

This taken directly by a lip with projected area $= 1/8 \times 49 = 55 \text{ in}^2$

$$\text{Bearing stress} = S_c = \frac{901,860}{55} = 16,400 \text{ PSI} \quad \text{OK } 30,000 \text{ Y.P.}$$

The load is taken directly edge-on into the cask top plate and into the head bottom plate acting in parallel to give very rugged construction in this plane.

REFERENCE:

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G.2. STUDS & NUTS ON CLOSURE HEAD.

LOAD CONDITIONS

- a. $901,860^{\#}$ = 15 X WT. LOADED CASK
b. $813,600^{\#}$ = 60 X WT. HEAD + CONTENTS CASK.
c. $194,500^{\#}$ = 100 PSI ON HEAD.
- } ON ULTIMATE STRESS
ON YIELD STRESS

24 studs and nuts are used to retain the head.

Studs are SA-193-B8 Strain hardened to 125,000 PSI ULT. T.S.

max. tension load per stud

$$\frac{901,860}{24} = 37,600^{\#}$$

area in tension = .3766 in².

for 3/4-10 threaded stud

$$\text{Tensile stress} = S_T = \frac{37,600}{.3766} = 115,000 \text{ PSI} \quad \text{OK } 125,000 \text{ PSI ULT.}$$

shear loads are taken on lips of head and cask.

NUTS are A194-GR8 FB and noted to be furnished strain hardened to 125,000 PSI min. tensile strength. Standard proportions of nuts insure adequate strength to equal that of the studs.

Thread strength in S.S. Flanges

This material has 30,000 Y.P.

Commercial nuts of this type are given a rating of 52,000[#] min with only 1 diameter engaged. Present studs have about 1 1/2 diameter engaged, with extra safety.

REFERENCE:

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7. STRUCTURAL INTEGRITY UNDER 100 PSI
(72.32d)

STRESSES NOT TO EXCEED YIELD STRESSES.

This section deals with plate and cylinder stresses only.
Studs and flanges are separately rated for this condition by references.
and are not critically stressed here.

7.1 CLOSURE HEAD BOTTOM PLATE

Refer to section 6 for sketch of closure head.

assume that lead is not bonded to bottom plate, but that
this has opportunity for some small deflection within a void.
Let design pressure be 100 PSI internally.

REFERENCE:

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7.1 (CONTINUED)

The following constants are from ASME tables for cylindrical vessels with flat plate closures. The stresses are greater for the flat plate.

For the flat plate $\frac{d}{t_h} = \frac{30}{1\frac{1}{8}} = 26.7$

$a_1 = -2.1 \times 26.7 = -56.$

$a_2 = +1.4$

$a_3 = +.06563 \times 26.7 = +1.71$

$b_1 = +1.27 \times 26.7 = +34.$

$b_2 = -.6355$

$b_3 = -.03972 \times 26.7 = -1.06$

For the cylinder

$\frac{t_h}{t_s} = \frac{1\frac{1}{8}}{2.88} = .39$

By interpolation based on $\frac{t_h}{t_s} = 1.0$

$\frac{d}{t_s} = \frac{30}{2.88} = 10.4$

$a_4 = -6.45$

$a_5 = -1.12$

$a_6 = -.083$

$b_4 = (.39)^2 (-5.7485) = -.875$

$b_5 = (.39)^2 (-.50) = -.076$

Substituting in

$$M_0 = pd^2 \frac{(a_3 - a_4)(b_5 - b_2) - (a_5 - a_3)b_3}{(a_4 - a_1)(b_5 - b_2) - (a_5 - a_3)(b_4 - b_1)}$$

$$= 100(30)^2 \frac{(+1.71 + .083)(-.076 + .6355) - (-1.12 - 1.4)(-1.06)}{(-6.45 + 56)(-.076 + .6355) - (-1.12 - 1.4)(-.875 - 34.)}$$

$$= 90,000 \left[\frac{(+1.793)(+.5595) - (-2.52)(-1.06)}{(+49.55)(+.5595) - (-2.52)(-34.875)} \right]$$

$$= 90,000 \left[\frac{+10 - 2.675}{+27.75 - 88} \right] = 90,000 \left(\frac{-1.675}{-60.75} \right) = +2500$$

$$Q_0 = pd \frac{(a_4 - a_1)b_3 - (a_3 - a_4)(b_4 - b_1)}{(a_4 - a_1)(b_5 - b_2) - (a_5 - a_3)(b_4 - b_1)}$$

$$= 100(30) \frac{(+49.55)(-1.06) - (+1.793)(-34.875)}{-60.75}$$

$$= 3000 \left(\frac{-52.6 + 62.45}{60.75} \right) = 3000 \left(\frac{+9.85}{-60.75} \right) = -491$$

For the flat plate

$$f_{\text{plate}} = \frac{3}{2} \frac{Q_0}{t_h} = \frac{3pd}{8t_h} = \frac{3(100)30}{8(1\frac{1}{8})} = 1000 \text{ psi}$$

$$f_{\text{total comb.}} = \left| \frac{Q_0}{t_h} \right| + \left| \frac{6M_0}{t_h^2} - \frac{3Q_0}{t_h} \right| = \left| \frac{-491}{1\frac{1}{8}} \right| + \frac{6(2500)}{(1\frac{1}{8})^2} - \frac{3(-491)}{1\frac{1}{8}}$$

$$= 436 + (11860 + 1310) = 436 + 13,170 = 13,606 \text{ psi max}$$

OK 90,000 psi sp.

$$f_{\text{circum. comb.}} = \left| \frac{Q_0}{t_h} \right| + \left| \frac{6M_0}{t_h^2} - \frac{3Q_0}{t_h} - 6p \left(\frac{d}{t_h} \right)^2 \left(\frac{1-m}{32} \right) \right|$$

$$= 436 + 13,170 - 6(100) \left(\frac{30}{1\frac{1}{8}} \right)^2 \frac{.20}{32}$$

$$= 13,606 - 9325 = 4281 \text{ psi}$$

The closure head is safe under 100 psi pressure.

REFERENCE:

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7.2

ANALYSIS OF VARIOUS PROPORTIONS

FOR INNER VESSEL.

$d = 30''$ SECTION AT T_s EFFECTIVE FOR LENGTH $8\frac{1}{2}''$

Coefficients are taken from ASME tables for cylindrical vessels with flat plate closures, as given in "Process Equipment Design", Brownell & Young, pg 108.

CASE	r_h	r_s	$\frac{r_h}{r_s}$	d/r_h	d/r_s	a_1	Flat Head Coefficients				
							a_2	a_3	b_1	b_2	b_3
A	1	$\frac{1}{2}$	2	30	60	-63.	+1.4	+1.97	+38.1	-.6355	-1.19
B	1	$\frac{3}{4}$	$\frac{4}{3}$	30	40	-63.	+1.4	+1.97	+38.1	-.6355	-1.19
C	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{5}{3}$	24	40	-50.5	+1.4	+1.58	+30.5	-.6355	-.95
D	$\frac{1}{2}$	$\frac{3}{4}$	2	20	40	-42.	+1.4	+1.31	+25.4	-.6355	-.79

General formulae

$$\beta = \sqrt[4]{\frac{12(1-\mu^2)}{d^2 T_s^2}}$$

$$= \sqrt[4]{\frac{12(91)}{30^2 T_s^2}}$$

$$\beta^2 = \frac{.11}{T_s}$$

$$\beta = \sqrt[4]{.382}$$

Hoop stress in $T_s =$

$$f_s = \frac{pd}{2T_s} = \frac{100 \text{ psi} \times 30''}{2T_s} = \frac{1500}{T_s}$$

axial tension in $T_s =$

$$f_a = \frac{pd}{4T_s} = \frac{100 \text{ psi} \times 30''}{4T_s} = \frac{750}{T_s}$$

$$M_0 = pd^2 \left[\frac{(a_3 - a_6)(b_5 - b_2) - (a_5 - a_2)b_3}{(a_4 - a_1)(b_5 - b_2) - (a_5 - a_2)(b_4 - b_1)} \right]$$

$$Q_0 = pd \left[\frac{(a_4 - a_1)b_3 - (a_3 - a_6)(b_4 - b_1)}{(a_4 - a_1)(b_5 - b_2) - (a_5 - a_2)(b_4 - b_1)} \right]$$

Shell combined stresses

$$f_{axial \text{ combined}} = \frac{pd}{4T_s} + \left| \frac{GM_0}{T_s^2} \right|$$

$$f_{circumferential \text{ combined}} = \frac{pd}{2T_s} + \left| \frac{3d(3M_0 + Q_0)}{T_s} \right| + \left| \frac{\mu GM_0}{T_s^2} \right|$$

β	CASE	a_4	Cylinder Coefficients			b_4	b_5	$b_6 = 0$
			a_5	a_6	a_7			
.469	A	-198.27	-14.08	-.425		-56.32	-2.	
.383	B	-88.06	-7.85	-.283		-20.77	-.90	
.383	C	-110.	-9.44	-.354		-32.03	-1.40	
.383	D	-132.18	-11.497	-.425		-45.98	-2.	

CASE	Hoop stress in shell	axial stress in shell
A	3000 psi	1500 psi
B	2000 psi	1000 psi
C	2000 psi	1000 psi
D	2000 psi	1000 psi

100 psi pressure

$$pd^2 = 90,000.$$

$$pd = 3000.$$

REFERENCE:

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7.2 (CONTINUED)

CASE	$(a_3 - a_6)$	$(b_5 - b_2)$	$(a_3 - a_6)(b_5 - b_2)$
A	$+1.97 + .475 = +2.395$	$-2.0 + .6355 = -1.3645$	-3.27
B	$+1.97 + .283 = +2.253$	$-.90 + .6355 = -.2645$	$-.597$
C	$+1.58 + .354 = +1.934$	$-1.40 + .6355 = -.7645$	-1.48
D	$+1.31 + .475 = +1.735$	$-2.0 + .6355 = -1.3645$	-2.37

	$(a_5 - a_2)$	b_3	$-(a_5 - a_2)b_3$
A	$-14.08 - 1.4 = -15.48$	-1.19	-18.4
B	$-7.85 - 1.4 = -9.25$	-1.19	-11.0
C	$-9.44 - 1.4 = -10.84$	$-.95$	-10.3
D	$-11.497 - 1.4 = -12.897$	$-.79$	-10.18

	$(a_4 - a_1)$	$(b_4 - b_1)$
A	$-198.27 + 63. = -135.27$	$-56.32 - 38.1 = -94.42$
B	$-88.06 + 63. = -25.06$	$-20.77 - 38.1 = -58.87$
C	$-110. + 50.5 = -59.5$	$-32.03 - 30.5 = -62.53$
D	$-132.18 + 42. = -90.18$	$-45.98 - 25.4 = -71.38$

CASE A
 $M_0 = 90,000 \left[\frac{-3.27 - 18.4}{(-135.27)(-1.3645) - (-15.48)(-94.42)} \right] = 90,000 \left[\frac{-21.67}{+184.9 - 1459.} \right] = 1530.$
 $Q_0 = 3,000 \left[\frac{(-135.27)(-1.19) - (+2.395)(-94.42)}{-1274.1} \right] = 3,000 \left[\frac{+161. + 226.}{-1274.1} \right] = -912.$

CASE B
 $M_0 = 90,000 \left[\frac{-.597 - 11.0}{(-25.06)(-.2645) - (-9.25)(-58.87)} \right] = 90,000 \left[\frac{-11.597}{+6.65 - 545.} \right] = 1900.$
 $Q_0 = 3,000 \left[\frac{(-25.06)(-1.19) - (+2.253)(-58.87)}{-538.35} \right] = 3,000 \left[\frac{+29.9 + 132.5}{-538.35} \right] = -904.$

CASE C
 $M_0 = 90,000 \left[\frac{-1.48 - 10.3}{(-59.5)(-.7645) - (-10.84)(-62.53)} \right] = 90,000 \left[\frac{-11.78}{+45.5 - 680.} \right] = 1670.$
 $Q_0 = 3,000 \left[\frac{(-59.5)(-.95) - (+1.934)(-62.53)}{-634.5} \right] = 3,000 \left[\frac{+56.5 + 121.}{-634.5} \right] = -840.$

CASE D
 $M_0 = 90,000 \left[\frac{-2.37 - 10.18}{(-90.18)(-2.37) - (-12.897)(-71.38)} \right] = 90,000 \left[\frac{-12.55}{+213.5 - 918.} \right] = 1602.$
 $Q_0 = 3,000 \left[\frac{(-90.18)(-.79) - (+1.735)(-71.38)}{-704.5} \right] = 3,000 \left[\frac{+71. + 123.5}{-704.5} \right] = -829.$

REFERENCE:

STRESS ANALYSIS

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7.2 (CONTINUED)

SHELL COMBINED STRESSES

$$f_{\text{axial}} = \frac{pd}{4t_s} + \left| \frac{6M_o}{t_s^2} \right| = \frac{750}{t_s} + \left| \frac{6M_o}{t_s^2} \right|$$

$$\text{Case A} \quad \frac{750}{1/2} + \frac{6(1530)}{(1/2)^2} = 1,500 + 36,750 = 38,250 \text{ psi}$$

$$\text{Case B} \quad \frac{750}{.75} + \frac{6(1900)}{.75^2} = 1000 + 20,250 = 21,250 \text{ psi}$$

$$\text{Case C} \quad \frac{750}{.75} + \frac{6(1670)}{.75^2} = 1000 + 17,800 = 18,800 \text{ psi}$$

$$\text{Case D} \quad \frac{750}{.75} + \frac{6(1602)}{.75^2} = 1000 + 17,100 = 18,100 \text{ psi}$$

$$f_{\text{circumferential}} = \frac{pd}{2t_s} + \left| \frac{3d(3M_o + Q_o)}{t_s} \right| + \left| \frac{46M_o}{t_s^2} \right|$$

$$\text{Case A} \quad \frac{1500}{.50} + \left| \frac{469(30)(469 \times 1530 - 912)}{.50} \right| + \frac{1.8 \times 1530}{.25} \\ = 3000 + \left| \frac{28.14(717 - 912)}{195} \right| + 11,000 = 3000 + 5500 + 11,000 = 19,500 \text{ psi}$$

$$\text{Case B} \quad \frac{1500}{.75} + \left| \frac{383(30)(383 \times 1900 - 904)}{.75} \right| + \frac{1.8 \times 1900}{.5625} \\ = 2000 + \left| \frac{15.3(728 - 904)}{176} \right| + 6095 = 2000 + 2690 + 6095 = 10,785 \text{ psi}$$

$$\text{Case C} \quad \frac{1500}{.75} + \left| \frac{383(30)(383 \times 1670 - 840)}{.75} \right| + \frac{1.8 \times 1670}{.5625} \\ = 2000 + \left| \frac{15.3(640 - 840)}{200} \right| + 5350 = 2000 + 3060 + 5350 = 10,410 \text{ psi}$$

$$\text{Case D} \quad \frac{1500}{.75} + \left| \frac{383(30)(383 \times 1602 - 829)}{.75} \right| + \frac{1.8 \times 1602}{.5625} \\ = 2000 + \left| \frac{15.3(614 - 829)}{215} \right| + 5130 = 2000 + 3290 + 5130 = 10,420 \text{ psi}$$

Final design is according to Case C, with max stress = 18,800 psi in shell.
Since the closure head is thicker its stresses are less.

The design is well below yield point stress of 30,000 psi.

Note that the closure plate was assumed to be a flat plate.

The addition of a standard knuckle radius decreases the above stresses.

REFERENCE:

STRESS ANALYSIS

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7.3 Outer shell - assumed under 100 PSI pressure.

$$\beta = \frac{1.28}{\sqrt{24}} = \frac{1.28}{\sqrt{24 \times 1}} = \frac{1.28}{4.899} = .262 \quad \beta l = .262 \times 93 = 24.4''$$

Since the beam deflection becomes 0 at $\beta x = 2.36$, only $\frac{x}{l} = \frac{2.36}{24.4} = .097$ part of shell height is expanded by local bending moment between the shell and the bottom plate. That is, the influence of the bottom plate extends

$$\beta x = 2.36 \quad x = \frac{2.36}{.262} = 9''$$

Tangential stress of cylinder at bottom is

$$S_T = \frac{Pr}{t} = \frac{100 \times 24}{1} = 2400 \text{ psi}$$

Radial expansion at the base of cylinder (if not attached to bottom plate)

$$\Delta r = \frac{ST}{E} r = \frac{2400}{29 \times 10^6} \times 24 = .00198''$$

Bending moment M in the shell at the bottom is

$$\frac{M}{y} = \frac{K}{2\beta^2} \quad \text{where } K = \frac{Et}{r^2} = \frac{29 \times 10^6 \times 1}{24^2} = 50,400$$

$$M = \frac{yK}{2\beta^2} = \frac{.00198 \times 50,400}{2(.262)^2} = 731 \text{ in-lbs per inch width unit strip}$$

$$\underline{\underline{Stress}} = \frac{6M}{t^2} = \frac{6 \times 731}{1^2} = \underline{\underline{4386 \text{ psi}}} \text{ tensile inside bottom shell.}$$

REFERENCE:

STRESS ANALYSIS

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8. STRUCTURAL INTEGRITY UNDER FIRE TEST.

This section deals with the question of void space and its requirements with rise in temperature, and the expansions of lead and steel during the fire test.

8.1 ANALYSIS OF EXPANSIONS DURING FIRE TEST. - CASE 1

<u>Initial</u>	<u>Final</u>		(see following sheets for referenced data quoted.) (FIRE ANALYSIS - Pg 46)
180°F	1200°	Temp. outer shell	
200	900	Temp. lead	
220	660	Temp inner shell	

Case is also assumed to have void space filled with lead at 200°F
 $96,052 \text{ in}^3$ gross volume of lead at 200°

Expansion of lead =

$$(96,052)(3 \times 16.3 \times 10^{-6})(900 - 200) = 3287.8 \text{ in}^3$$

$$(96,052)(.036) = 3457.8 \text{ in}^3$$

$$V_L = 6,745.6 \text{ in}^3$$

temp. rise.
melting expansion

Expansion of steel - outer shell

$$(160,695)(3 \times 6.7 \times 10^{-6})(1200 - 180) = 3294.5 \text{ in}^3 = V_o$$

Expansion of steel - inner shell

$$(64,643)(3 \times 6.7 \times 10^{-6})(660 - 220) = 571.7 \text{ in}^3 = V_i$$

Final increase in volume of inner shell

$$\begin{array}{r} 571.7 \\ \text{plus lead} \quad + 6745.6 \\ \hline 7217.3 \text{ in}^3 \end{array}$$

minus outer shell

$$\begin{array}{r} 7217.3 \\ - 3294.5 \\ \hline 3922.8 \text{ in}^3 \end{array}$$

Let this change in volume

be applied to a cylinder 80" long x 47" I.D.

$$\text{Then } (80 \times .785 \times 47^2) 3\alpha = 3922.8 \text{ in}^3$$

$$\alpha = \frac{3922.8}{80 \times 1734.94 \times 3} = .00945 \text{ linear expansion factor}$$

This corresponds to $.00945 \times 30 \times 10^6 = 283,500 \text{ PSI}$ stress - if material allows.
 For 30,000 PSI y.p. steel, this means the material has been stretched beyond its yield point and has been given a permanent set of about 1% elongation. This value is so low as to insure relatively uniform expansion, with consequent integrity at the conclusion.

The following calculations provide data under other conditions of heating.

REFERENCE:

STRESS ANALYSIS

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8.2

STRESS CONDITIONS DURING FIRE TEST.

(BASED ON BULK TEMP ANALYSIS)

The thermal analysis has determined that, with an absorptivity coefficient as high as .80 during exposure to the calculated furnace conditions of the "Standard Fire Test", the final mean temperature would be 785°F , with the lead completely molten. (Fire Analysis Page 42)

The question now is what happens as a result of the expansion of the lead. This is answered by considering, first, the volume increase to be accommodated and second, the void capacity available and third the stresses resulting from hydraulic distortion of the shell on continued expansion.

Volume of lead in cask.

This is present in the form of an annulus plus a slab plate.

$$\text{Vol} = \frac{\pi}{4} (47^2) \times 92.62 - \frac{\pi}{4} (31^2) \times 85.62$$

$$= 1735 \times 92.62 - 755 \times 85.62$$

$$= 160,695 - 64,643 = \frac{96,052 \text{ in}^3}{1060 \text{ m}^3} \text{ gross void}$$

$$95,000 \text{ m}^3 \text{ Net lead volume.}$$

$$\text{Void Volume} = (2\pi \cdot 22) 7.66$$

$$= \underline{1060 \text{ m}^3}$$

% Void Volume

$$\text{Cask } \frac{1060}{95000} = .01115$$

$$\text{Closure } \frac{130}{10210} = .01273$$

Volume of lead in closure head

$$\underline{10,210 \text{ m}^3 \text{ Net lead volume}}$$

REFERENCE:

STRESS - FIRE TEST ANALYSIS

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B.2 (CONTINUED)

Expansion Volume Required

Temperature conditions

180°F mean temperature of cask at start of Standard Fire Test

475°F max. normal temperature

300° = Δt_1 Nominal rise in temp. for normal conditions.

785°F max. temp. at end of 1-hour Fire Test

605° = Δt_2 Nominal rise in temp. during Fire Test

Expansion of lead and steel

$$\begin{array}{rcl} 16.3 \times 10^{-6}/^{\circ}\text{F} & \text{max. value for lead} & \\ - 6.7 \times 10^{-6}/^{\circ}\text{F} & \text{max. value for steel} & \\ \hline 9.6 \times 10^{-6}/^{\circ}\text{F} & \text{Differential coef. (lead-steel)} & \end{array} \left. \vphantom{\begin{array}{rcl} 16.3 \times 10^{-6}/^{\circ}\text{F} \\ - 6.7 \times 10^{-6}/^{\circ}\text{F} \\ \hline 9.6 \times 10^{-6}/^{\circ}\text{F} \end{array}} \right\} \text{Linear coef.}$$

In addition a 3.6% volume increase occurs during melting of lead.

Increase in volume of lead (Excess of lead increase over steel increase)

For 300° = Δt_1 , $3(9.6 \times 10^{-6}) \times 300^{\circ} = .00864$

Closure Head

$$10,210 \text{ m}^3 \times .00864 = 88.2 \text{ m}^3 \quad \text{OK Void} = 130 \text{ m}^3$$

Cask Body

$$95,000 \text{ m}^3 \times .00864 = 820.8 \text{ m}^3 \quad \text{OK Void} = 1060 \text{ m}^3$$

For 605° = Δt_2 and including growth on melting

Closure Head

$$3(9.6 \times 10^{-6}) \times 605^{\circ} = .017424$$

$$\begin{array}{r} 3.6\% \text{ volume} \\ \text{change on melting} \end{array} = \frac{.036}{.053424}$$

$$10,210 \text{ m}^3 \times .053424 = 545.4 \text{ m}^3$$

$$\begin{array}{r} 545.4 \text{ m}^3 \\ - 130. \text{ m}^3 \text{ Void} \\ \hline 415.4 \text{ m}^3 \end{array}$$

shell expansion required

Cask Body

$$95,000 \text{ m}^3 \times .053424 = 5075 \text{ m}^3$$

$$\begin{array}{r} 5075 \text{ m}^3 \\ - 1060 \text{ m}^3 \text{ Void} \\ \hline 4015 \text{ m}^3 \end{array}$$

shell expansion required

REFERENCE:

STRESS-FIRE TEST ANALYSIS

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8.2 Fire Test Expansion of Outer Shell

(CONTINUED)

Cask Body is required to accommodate 4015 in^3 increase in contained volume. This can be accomplished by means of

- 1) Contraction in volume of lead under hydrostatic pressure.

Even under 1000 psi pressure this is negligible.

K = bulk modulus of elasticity for lead

$$= \frac{E}{3(1-2\mu)} = \frac{2.2 \times 10^6}{3(1-2 \times .43)} = \frac{2.2 \times 10^6}{.42} = 5.23 \times 10^6$$

$$\frac{1000 \text{ psi}}{5.23 \times 10^6 \text{ psi}} = .000,1912 = \text{unit volume contraction at 1000 psi}$$

$$95000 \text{ in}^3 \times .000,1912 = 18.16 \text{ in}^3 - \text{negligible}$$

- 2) Compression of inner shell - cylindrical wall

This is very rigid against external pressure, at least over the length of the cylinder itself. Its own resistance to compression stress is combined with the physical support from the basket.

Assume, conservatively, that this is not in itself in danger, and that it does not contribute to the needed increase in lead cavity volume.

$$\text{Hoop Stress} = \frac{1000 \times 15.5'' R}{t = 1/2''} = 31,000 \text{ psi (nominal y.p.)}$$

The backup action of the basket in the region where the thickness is reduced to $t = 1/2''$ will prevent instability as well as contraction beyond the small clearance allowed.

- 3) The remaining areas of steel shell which can be distorted to provide the required growth of lead content are the flat plate closures of the cover itself, of the inner and outer shells of the cask, and the outer cylinder of the cask.

In general, to gain plastic distortion in the outer cylinder, a hydrostatic pressure sufficient to give a hoop stress of 30,000 psi is required

$$\text{Hoop stress} = 30,000 \text{ psi} = \frac{P \times 47/2}{t = 1''}$$

$$P = 30,000 \times 1 \times \frac{2}{47} = \underline{1276 \text{ psi}}$$

Therefore, plastic failure - or at least, plastic distortion of the flat plate areas can be expected before the outer wall will stretch.

REFERENCE:

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8.3 Brownell and Young in "Process Equipment Design" have this to say about the present problem of the plastic distortion of the flat plate closures. Both the plates in the bottoms of the inner and outer shells of the cask have knuckle radii and for this reason are responsive to the following - (quoted from page 136, par 7.11)

"Fig. 7.17 indicates the permanent set produced when such a head is plastically deformed. The crown expands outward, the knuckle flattens, and the profile becomes more elliptical. As a result of this plastic deformation, the head becomes stronger with a redistribution of the stresses."

FIG 7.17 (b)

Elastic theory does not permit the calculation of such stresses after plastic set has occurred. Therefore, it has been necessary to use experimental tests of vessel failures to establish an empirical correlation for the design of tori-spherical heads."

The conditions during the fire test are different from those imposed by the dynamic conditions of impact. The latter case develops severe gradients in hydrodynamic pressures, while in the fire test a uniform distribution of internal pressure from the head is of advantage. Therefore, since the bottom external closure is thicker than the outer cylinder wall, it is reasonable to assume that the cylinder walls can assist by yielding plastically under internal pressures which deform and strengthen the closure head, without having exceeded, in plastic strain rather than stress, the rupture point of the knuckle itself. To quote further,

"The meridional and hoop stresses are of opposite signs at the inner surface of the knuckle. Large shearing stresses and strains exist at an angle of 45° with the meridionals but no case of failure had occurred which could be attributed to these strains. The cracks that were observed always occurred along a ring in the knuckle."

This emphasizes the importance of sound material and an absence of such "rings" as could cause splits in aggravated conditions such as the fire test and shock tests.

REFERENCE:

STRESS-FIRE TEST ANALYSIS

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8.4 The conclusion appears justified that the present proportions of design allow a sufficient mass of steel in wide distribution to allow of plastic strain without such local excessive strains as would result in rupture. To get a better understanding of the relatively small amount of stretch required to accommodate the increase in lead volume, consider the degree of plastic strain developed if only 80" length of the outer shell were hydrostatically distended to provide an additional 4015 m^3 displacement.

Excess volume to be developed per inch of cylinder length is

$$\frac{4015 \text{ m}^3}{80"} = 50.2 \text{ m}^3/\text{in}$$

Present I.D. = 47" with area = 1735 m^2

at a temperature of 985° this I.D. has expanded to

$$47(1 + 605 \times 6.7 \times 10^{-6}) = 47(1 + .004355) = 47.2047"$$

with an area of $1750. \text{ m}^2$

$$\frac{50.2 \text{ m}^2}{1800.2 \text{ m}^2} \text{ is the required increase in area}$$

$$= \frac{1}{4} (47.875)^2$$

The ratio of diameters is

$$\frac{47.8750}{47.2047} = 1.0142$$

Therefore, the shell has had to expand only 1.42% elongation in regard to hoop strain to accommodate the total required lead expansion with low carbon steel, about 20x this elongation would be conservative before rupture would take place.

Since both closure plates would also partake of the total volume displacement required for the lead expansion, the cask is presumed safe during the fire test.

For the cask top closure head, similar distortion would be required in the two plate members, to accommodate, in this case, however, only 415.4 m^3 . The following study was made for the 46" I.D. lower flat plate.

As a simplified model, from which 371 m^3 was expected, it shows, to scale, only .678" center deflection required.

For the upper plate, 1" thick, 371 m^3 are provided by this deflection at a pressure of 412 psi, and approx the full 415.4 m^3 at 460 psi, (hydraulic pressure).

It is concluded that the cask design is safe during the fire test.

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Flat Plate (Rank, case 6, table X)
Edges fixed.
Uniform load over entire surface

$$y = -\frac{3W(m^2-1)}{16\pi E m^2 t^3} \left[\frac{(a^2-r^2)^2}{a^2} \right] = \lambda \left[\frac{(a^2-r^2)^2}{a^2} \right] \quad \therefore \frac{y a^2}{\lambda} = (a^2-r^2)^2$$

$$\text{Volume of space } V = \pi \int_0^{y'} r^2 dy \quad \text{where} \quad a \sqrt{\frac{y}{\lambda}} = a^2 - r^2$$

$$r^2 = a^2 - \frac{a}{\sqrt{\lambda}} \sqrt{y}$$

$$= \pi \int_0^{y'} \left(a^2 - \frac{a}{\sqrt{\lambda}} \sqrt{y} \right) dy$$

$$V = \pi \left(a^2 y' - \frac{a}{\sqrt{\lambda}} \frac{2}{3} y'^{3/2} \right) = \pi \left(a^2 y' - \frac{a}{\sqrt{\lambda}} \frac{2}{3} y'^{3/2} \right)$$

let $a = 23''$
 $V = 370.8 \text{ in}^3$
 $t = 3/4''$

$$\lambda = \frac{-3W(m^2-1)}{16\pi E m^2 t^3} = \frac{-3W \left(\left(\frac{1}{.30} \right)^2 - 1 \right)}{16\pi 29 \times 10^6 \left(\frac{1}{.30} \right)^2 \left(\frac{3}{4} \right)^3} = \frac{3W(10.11)}{1460 \times 10^6 (11.11)(.4218)}$$

$$\therefore \lambda = .00442 W \times 10^{-6}$$

$$V = \pi \left(529 y' - \frac{23}{.0665 \sqrt{W}} y'^{3/2} \right) = 1660 y' - \frac{230,000 y'^{3/2}}{\sqrt{W}}$$

let $V = 370.8 \text{ in}^3$

$$y' \text{ at center} = -\frac{3W(m^2-1)a^2}{16\pi E m^2 t^3} = \lambda a^2$$

$$\text{or } V = \pi \left(a^2 \lambda a^2 - \frac{a}{\sqrt{\lambda}} \frac{2}{3} (\lambda a^2)^{3/2} \right)$$

$$= \pi \left(a^4 \lambda - \frac{2}{3} \frac{a}{\sqrt{\lambda}} \lambda^{3/2} a^3 \right) = \pi a^4 \lambda - \pi \frac{2}{3} \lambda a^4 = \frac{\pi}{3} \lambda a^4$$

$$\therefore 370.8 = \frac{\pi}{3} (.00442 W \times 10^{-6}) 23^4$$

$$= .00462 W \cdot 2798 = .00128 W$$

$$\therefore W = \frac{370.8}{.00128} = 289,500 \text{ lb}$$

$$W = w \pi a^2 = w 1662$$

$$w = \frac{289,500}{1662} = 174 \text{ psi}$$

checking $\max y = -\frac{3(289,500) \left(\left(\frac{1}{.32} \right)^2 - 1 \right) 23^2}{16\pi 29 \times 10^6 \frac{1}{.32} \left(\frac{3}{4} \right)^3} = \frac{4640 \times 10^6}{6840 \times 10^6} = .678''$

Case for $t = 1''$ $w = \left(\frac{1}{.75} \right)^3 \times 174 \text{ psi} = 412 \text{ psi}$

$t = 1\frac{1}{4}''$ $w = \left(\frac{1.25}{.75} \right)^3 \times 174 \text{ psi} = 806 \text{ psi}$

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8.4(Cont)

$$y \text{ at any radius } r = y_{\max} \times \left[\frac{(a^2 - r^2)^2}{a^4} \right] \text{ where } a = 23", a^2 = 529, a^4 = 279,841$$

$$\frac{y}{y_{\max}} = \frac{(a^2 - r^2)^2}{a^4} = \frac{(529 - r^2)^2}{279,841}$$

$$\text{let } r = 0 \quad \frac{y}{y_{\max}} = \frac{529^2}{279,841} = 1$$

$$y = 1 \times 0.678 = 0.678"$$

$$r = 5 \quad = \frac{(529 - 25)^2}{279,841} = \frac{254,016}{279,841} = .907$$

$$y = .907 \times 0.678 = .615"$$

$$r = 10 \quad = \frac{(529 - 100)^2}{279,841} = \frac{184,041}{279,841} = .657$$

$$y = .657 \times 0.678 = .446"$$

$$r = 15 \quad = \frac{(529 - 225)^2}{279,841} = \frac{97,416}{279,841} = .33$$

$$y = .33 \times 0.678 = .224"$$

$$r = 17 \quad = \frac{(529 - 289)^2}{279,841} = \frac{57,600}{279,841} = .206$$

$$y = .206 \times 0.678 = .140"$$

$$r = 20 \quad = \frac{(529 - 400)^2}{279,841} = \frac{16,641}{279,841} = .0595$$

$$y = .0595 \times 0.678 = .040"$$

Section	Area	Arm	Mom. Area
1	$.650 \times 5 = 3.25 \text{ in}^2$	$\frac{6.57}{6.78} \times 2.5 = 2.42$	7.860
2	$.535 \times 5 = 2.675$	$\frac{5.60}{6.15} \times 2.5 + 5.0 = 2.28 + 5.0 = 7.28$	19.45
3	$.385 \times 5 = 1.925$	$\frac{3.12}{4.45} \times 2.5 + 10.0 = 2.09 + 10.0 = 12.09$	20.22
4	$.182 \times 2 = .364$	$\frac{1.96}{3.20} \times 1.0 + 15 = .875 + 15 = 15.875$	5.77
5	$.088 \times 3 = .264$	$\frac{1.07}{1.40} \times 1.5 + 17 = 1.15 + 17 = 18.15$	4.80
6	$.04 \times 1 = .04$	$\frac{.04}{.140} \times 1.5 + 21 = .21 + 21 = 21.21$	.84
	<u>8.268 in²</u>	C.G. at $\frac{58.94}{8.268} = 7.13"$	<u>58.94</u>

$$\text{Volume} = 8.268 (2\pi) 7.13$$

$$= \underline{371 \text{ in}^3} ! \quad (370.8 \text{ ASSUMED})$$

REFERENCE:

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SECTION VI
FIRE ANALYSIS

FURNACE CONDITION ANALYSIS

FLAME TIME-TEMPERATURE CURVE

CASK BULK TEMPERATURE ANALYSIS

CASK WALL GRADIENT ANALYSIS

REVISED

METHOD OF EVALUATING TIME-TEMPERATURE DATA
FOR STANDARD FIRE TEST CALCULATIONS.

The time-temperature data given as ASTM standard for control of fire tests are intended to be the thermocouple readings during the test. The thermocouples are enclosed in a one foot effective length of $\frac{1}{2}$ inch pipe and are located within the "furnace" and close to, but not touching, the object to be heated in the test.

The purpose of this section is to explore the problem of most accurately calculating the heat absorption of the cast itself when subjected to such a standard fire test. The problem immediately becomes highly involved and subject to a variety of irrelevant assumptions - unless full advantage is taken of the one opportunity for a satisfactory solution. It is specified quite precisely that the time response of the $\frac{1}{2}$ " pipe shall be a definite temperature curve.

It is intended, therefore, that this pipe shall provide sufficient data to determine the radiating and convective heating characteristics of the ambient "furnace" surround, and that in turn, this knowledge shall allow calculation of still another body (the cast) also submerged in the "furnace." Evidently, the data must be relevant to the heat received by the pipe and cast, rather than to the emission etc. of the furnace.

Fortunately, there seems to be sufficient related information available to allow a method to be developed which puts emphasis on the characteristics by which the two bodies are related (these being largely known) and allows avoiding most of the complexities of heat source considerations.

The only questionable area in the whole method - and one which cannot be side-stepped - is that concerning the convective coef. (h_c). This is studied from several approaches, both singly and in combination with (h_r), and it is believed a very satisfactory basis for estimate is secured.

It must be kept in mind that it is the final state in which we are interested and not any particular interim conditions. It may be desirable, therefore, after following a close analysis, point by point, to develop and apply some new formula by which the end condition may be more easily and directly estimated, possibly a direct function of degree minutes, but with the necessary inclusion of sophisticated data related to pipe and cast and furnace.

REFERENCE:

FIRE TEST ANALYSIS

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There are, of course, further studies which may be made after the conclusion of this analysis.

- 1) The thermal conductivity of the cast has been assumed as sufficient to eliminate present consideration of temperature differentials through the cast. A mean cast temperature (T_K) is used throughout.
- 2) The fire test specifies the control points to be 6-12 inches away from contact with the cast. Differences between these readings and those of skin bonded pickups is not a present concern.
- 3) Behavior of the lead in expanding during the fire test is a part of this section, but the detail mechanism of how lead moves within the cast under the slow time influence of heat has been avoided.

The present study and detail thermal analysis is a repetitive procedure which might well be required for each new design proposed. To obviate the need for repeating such lengthy calculations in order to determine the maximum cast temperature, a simplified formula is proposed.

It seems that since the direct radiation from a furnace "environment" has been largely indicated - but not directly specified - and since this form of heat transfer is dominant in this case, it would be most expedient to go a step further and reduce the fire test requirement to an equally discriminating analysis of much simpler application.

The suggestion is made, therefore, that an explanation of and reference to, this method and formula could be included in the specifications for new design studies, with considerable benefit.

REFERENCE:

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2. EVALUATION OF (h_r) IN $[h_r A_r (T_1 - T_2)]$

2.1 The general formula for radiant heat transmission involves the fourth power of two temperatures (absolute) and in such form is not adapted for combining coefficients with convective heat transmission, when the first power temperature expression of the latter is desired as the base. The present purpose is, therefore, to express radiant heat quantities in terms of $(T_1 - T_2)$ rather than $(T_1^4 - T_2^4)$. In another paragraph the alternate conversion will be discussed, namely, that of expressing convective coefficients in terms of $(T_1^4 - T_2^4)$.

The emissivity of the lower temperature body (being heated) is combined with its absorptivity in the presence of a heating source, (called the "furnace") expresses the net heat received radiantly by the body from the furnace.

$$q_{\text{radiant}} = \alpha F A_r \sigma T_{\text{furnace}}^4 - \epsilon F A_r \sigma T_{\text{body}}^4$$

The absorptivity α of the body for radiation from a source such as the furnace at temperature T_{furnace} is approximately equal to its emissivity at the latter temperature. The emissivity of the body at its own, and lower, temperature may be different, and for this reason both α and ϵ are shown independently.

The area A_r in both terms is the radiating area of the body. All reference to dimensional characteristics of the heat source must be eliminated in this particular case, for simplicity, and the assumption is made that, since we are measuring the heat received by the body, we can justify making our radiating "furnace" a simple black source (or gray source) not identified except by its temperature and flux conditions.

The factor F is taken as unity, its effect being included in the effective temperature which is taken as representing the heat source at any given instant of time.

For the thermocouple pipe, but not for a heavy cast body, α may be assumed equal to ϵ , due to a small differential of temp.

REFERENCE:

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2.2 Elements of Heat Transfer - Jakob - Hawkins

(p 218)

$$\phi_s = \sigma A T^4$$

where ϕ_s = time rate of radiated energy

A = radiating area

T = absolute temp. ($^{\circ}F + 460^{\circ}$)

σ = Stefan-Boltzmann's natural constant

$$= .174 (10^{-8}) \text{ B hr}^{-1} \text{ ft}^{-2} \text{ F}^{-4}$$

(or more recently .1714)

$$\therefore \phi = .174 A \left(\frac{T}{100}\right)^4$$

for black bodies only

For gray radiators

$$\phi_g = E_g \sigma A T^4$$

$$= E .174 A \left(\frac{T}{100}\right)^4$$

P 231

$$\therefore q_{12} = E_1 \sigma A_1 (T_1^4 - T_2^4) \quad \text{BTU/hr from interaction by reflection radiation.}$$

P 238

Combined convection and radiation 3

Rate of heat flow from outer surface 2 to wall temp 3 is

$$q = h_c A_2 (T_2 - T_3) + E_2 \sigma A_2 (T_2^4 - T_3^4) \quad \text{[radiation] 2 to 3}$$

h_c = coeff of heat transfer due to convection

Heat flows from surface 1 to outer surface 2 according to

$$q = \frac{K 2\pi L (T_1 - T_2)}{\ln(r_2/r_1)} \quad \text{[conduction] 1 to 2}$$

Combining and substituting value of σ

$$q = h_c A_2 (T_2 - T_3) + .174 E_2 A_2 \left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_3}{100}\right)^4 \right]$$

P 239

Combining coefficients of Convection and Radiation

$$\text{let } q_2 = h_2 A_2 (T_2 - T_3) \quad \text{where } h_2 = E_2 \sigma (T_2^2 + T_3^2)(T_2 + T_3)$$

$$\therefore q = h_c A_2 (T_2 - T_3) + h_2 A_2 (T_2 - T_3) = (h_c + h_2) A_2 (T_2 - T_3)$$

Per linear foot,

$$q' = \frac{q}{L} = \frac{K 2\pi (T_1 - T_2)}{\ln r_2/r_1} = (h_c + h_2) 2\pi r_2 (T_2 - T_3)$$

$$\therefore (h_c + h_2) = \frac{K (T_1 - T_2)}{r_2 (T_2 - T_3) \ln r_2/r_1}$$

(see table XII - 1 p 239)

REFERENCE:

REFERENCE FORMULAE - HEAT TRANSFER
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2.3 In the case of the thermocouple pipe, which is our only information source of the characteristics of our "furnace", the equation reduces to

$$q_{\text{pipe}} = \epsilon A_2 \sigma (T_f^4 - T_p^4) = \epsilon A \sigma (T_f^4 - T_p^4)$$

Further, since no fins are involved here, $A_2 = A_c = A$

The desired form is

$$q_{\text{pipe}} = h_2 A (t_f - t_p) \quad \text{from which}$$

$$h_2 = \frac{\epsilon A \sigma (T_f^4 - T_p^4)}{A (t_f - t_p)} = \frac{\epsilon \sigma (T_f^4 - T_p^4)}{(t_f - t_p)} = \epsilon \sigma \frac{(T_f^4 - T_p^4)}{(\Delta t)_p}$$

The expression may be left in this form, or reduced to terms of °F.

$$h_2 = \epsilon \sigma \frac{[(T_f^2 + T_p^2)(T_f + T_p)(T_f - T_p)]}{t_f - t_p}$$

Introducing $\epsilon = .90$ (assumed) and $\sigma = .174 \times 10^{-8}$

$$h_2 = \frac{.1566}{100} \left[\left(\frac{T_f}{100} \right)^2 + \left(\frac{T_p}{100} \right)^2 \right] \left[\frac{T_f}{100} + \frac{T_p}{100} \right] \quad \text{or } \frac{.1566}{100} [R_2][R_1] \quad \text{as used below}$$

This represents a family of curves based on a choice of T_p values.

$$T_p = t_p + 460$$

$$T_f = t_f + 460$$

$$(\Delta t)_p = (t_f - t_p)$$

Table T₁

t_p °F	$(\Delta t)_p$	t_f °F	T_f °R	$\left(\frac{T_f}{100}\right)^2 + \left(\frac{T_p}{100}\right)^2 = [R_2]$	$\left(\frac{T_f}{100}\right) + \left(\frac{T_p}{100}\right) = [R_1]$	$\frac{.1566}{100} [R_2][R_1]$	h_2
68	50	118	578	5.78	5.28	11.06	106
	100	168	628	6.28	"	11.56	1.22
	150	218	678	6.78	"	12.06	1.39
	200	268	728	7.28	"	12.56	1.59
	300	368	828	8.28	"	13.56	2.04
	400	468	928	9.28	"	14.56	2.60
	500	568	1028	10.28	"	15.56	3.25
	600	668	1128	11.28	"	16.56	4.03
	700	768	1228	12.28	"	17.56	4.91
	800	868	1328	13.28	"	18.56	5.95
	900	968	1428	14.28	"	19.56	7.10
	1000	1068	1528	15.28	"	20.56	8.40
	1100	1168	1628	16.28	"	21.56	9.88
	1200	1268	1728	17.28	"	22.56	11.52

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2.3 For $T_p = 240^\circ F \equiv 700^\circ R$

CONT.

Table
T₂

$(\Delta T)_p$	$T_f ^\circ F$	$T_f ^\circ R$	$(\frac{T_f}{100}) + (\frac{T_p}{100}) = [R_1]$	$(\frac{T_f}{100})^2 + (\frac{T_p}{100})^2 = [R_2]$	h_2				
50	290	750	7.5	7.0	14.5	56.25	49.	105.25	2.39
100	340	800	8.0	"	15.0	64.	"	113.	2.66
200	440	900	9.0	"	16.0	81.	"	130.	3.26
400	640	1100	11.0	"	18.	121.	"	170.	4.79
600	840	1300	13.	"	20.	169.	"	218.	6.83
800	1040	1500	15.	"	22.	225.	"	274.	9.42
1000	1240	1700	17.	"	24.	289.	"	338.	12.70
1200	1440	1900	19.	"	26.	361	"	410.	16.7

For $T_p = 60^\circ F \equiv 540^\circ R$

Table
T₃

$(\Delta T)_p$									h_r
50	130	590	5.9	5.4	11.3	34.81	29.16	63.97	1.13
100	180	640	6.4	"	11.8	40.96	"	70.12	1.29
200	280	740	7.4	"	12.8	54.76	"	83.92	1.68
400	480	940	9.4	"	14.8	88.36	"	117.52	2.73
600	680	1140	11.4	"	16.8	130.	"	159.16	4.20
800	880	1340	13.4	"	18.8	179.56	"	208.72	6.15
1000	1080	1540	15.4	"	20.8	237.2	"	266.36	8.69
1200	1280	1740	17.4	"	22.8	302.76	"	331.92	11.85

For $T_p = 400^\circ F \equiv 860^\circ R$

Table
T₄

$(\Delta T)_p$									h_h
50	450	910	9.1	8.6	17.7	82.81	73.96	156.77	4.34
100	500	960	9.6	"	18.2	92.16	"	166.12	4.75
200	600	1060	10.6	"	19.2	112.36	"	186.32	5.60
400	800	1260	12.6	"	21.2	158.76	"	232.72	7.73
600	1000	1460	14.6	"	23.2	213.16	"	287.12	10.42
800	1200	1660	16.6	"	25.2	275.56	"	349.52	13.79
1000	1400	1860	18.6	"	27.2	345.96	"	419.92	17.89
1200	1600	2060	20.6	"	29.2	424.36	"	498.32	22.76

For $T_p = 800^\circ F \equiv 1260^\circ R$

Table
T₅

$(\Delta T)_p$									h_2
50	850	1310	13.1	12.6	25.7	171.61	158.76	330.37	13.3
100	900	1360	13.6	"	26.2	184.96	"	343.72	14.1
200	1000	1460	14.6	"	27.2	213.16	"	371.92	15.85
400	1200	1660	16.6	"	29.2	275.56	"	434.32	19.85

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$(\Delta T)_s$ 2.4

$h_c + h_r$
= 8.40
for 1/2" IPS.
(MARKS)
@ $\Delta T = 800^\circ$

$h_r = 6.15$

$h_c = 2.25$

FLAT VERT. PLATE

24" PIPE

2" PIPE

1/2" PIPE

$(h_c + h_r)$
4 curves
@ $T_p = 80^\circ$

① h_r @ $T_p = 80^\circ$

h_r @ $T_p = 240^\circ$

h_r @ $T_p = 400^\circ$

h_r @ $T_p = 800^\circ$

$(h_c + h_r)$ 4 curves (STILL AIR @ $80^\circ F$)
from Marks (OXIDIZED BARE STEEL)

(h_r) only ~ 4 curves (from tables T_2, T_3, T_4, T_5)

Note that curve ① is basic, with (h_c) additive to it in approximately uniform amounts.

h_c AND h_r CURVES

FIG. 1

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2.5 As a further check on the probable accuracy of this method, note especially the trend displayed in the ratios

$$(h_c + h_r) = K(h_r)$$

In the previous examples K is involved as follows, -

(ΔT)	1/2" I.P.S.	55" I.P.S.
600°	$K = 1.475$	
1200°	$K = 1.27$	$K = 1.23$

Substantial support to the use, or at least, the interpretation, of K values is given in both Marks and McAdams in "Simplified Treatment of Combustion - chamber Heat Transmission", with the comments on Billet-reheating Furnaces, and a modification of the generalized equation in regard to

1) q is heat transferred to the stock, not from the flame.

(This is a most important factor already a part of the proposed new method)

2) convection terms have been omitted and

3) to compensate therefore and to allow for steadiness of furnace operation, (and using nomenclature of this report)

$$h_c + h_r = 1.2 h_r \quad \text{or } K = 1.2$$

Note that here we have specific evidence in the case of convected heat flow into the body from the furnace, whereas the previous data in regard to h_c referred to hot body radiation in the opposite direction.

The effect of turbulence and velocity of gas travel has not yet been considered. For the case of the cast in the fire test, we are attempting to establish the unwritten but implied specifications of the furnace "which is to heat our cast, and we must learn everything possible from its effects on the control tube, our 1/2 I.P.S. pipe. Both will therefore be subjected to the same turbulent conditions, and we may be well justified in saying that such conditions are adequately included in generic (h_r) values.

Commenting on the billet reheating value of $K = 1.2$ it must be accepted that the billet would have no fins and that its furnace temps. would probably be continuously at a maximum, providing relatively greater h_r importance. For this reason, the above values of K for pipe & cast seem appropriate.

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3.1 VALUES FOR (h_c) ESTIMATED TO BE INCLUDED IN ($h_c + h_r$) BY MARKS ETC

From table T_3 at $T_p = 80^\circ$, values of (h_r) are subtracted from ($h_c + h_r$) by Marks.

	$(\Delta T)_p - (h_r)_{\text{Table } T_3} + (h_c + h_r)_{\text{Marks}}$		$\frac{1}{2}" \text{ I.P.S.} = h_c$		$4" \text{ I.P.S.} = h_c$		$24" \text{ I.P.S.} = h_c$		$\text{VERT PLATE} = h_c$	
Table H_1	50	1.13	2.12	.99	1.84	.71	1.64	.31	1.82	.69
	100	1.29	2.48	1.19	2.16	.87	1.93	.64	2.13	.84
	200	1.68	3.10	1.42	2.72	1.04	2.45	.77	2.70	1.02
	400	2.73	4.47	1.74	4.02	1.29	3.70	.97	4.00	1.27
	600	4.20	6.24	2.01	5.72	1.52	5.37	1.17	5.70	1.50
	800	6.15	8.40	2.25	7.89	1.74	7.52	1.37	7.86	1.71
	1000	8.69	11.20	2.51	10.66	1.97	10.78	1.59	10.64	1.95
	1200	11.85	14.65	2.80	14.09	2.24	13.70	1.85	14.06	2.21

Jakob and Hawkins (Table VII-1) give different values of h_c for same tubes.

	$(\Delta T)_p$ Table T_3		$1.3" \text{ DIA}$ ($\approx 1" \text{ I.P.S.}$) h_c		$3.5" \text{ DIA}$ ($\approx 3" \text{ I.P.S.}$) h_c		$5.6" \text{ DIA}$ ($\approx 5" \text{ I.P.S.}$) h_c		$10.75" \text{ DIA}$ ($\approx 10" \text{ I.P.S.}$) h_c	
Table H_2	50	1.13	2.26	1.13	2.05	.92	1.95	.82	1.87	.74
	100	1.29	2.50	1.21	2.25	.96	2.15	.86	2.07	.78
	200	1.68	3.00	1.32	2.73	1.05	2.61	.93	2.54	.86
	400	2.73	4.34	1.61	4.03	1.30	3.90	1.17	3.84	1.11
	600	4.20	6.05	1.85	5.71	1.51

FIGURE 2 INITIAL VALUES OF h_c and h_r for body at 80°F

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3.2 The values of (h_c) in Figure can be quite conveniently and reasonably accurately represented by

$$h_c = \frac{1.05}{D^{1/4}} + \frac{\Delta T}{800}$$

This is directly applicable to the case of the thermocouple pipe when radiating heat as a hot body, since it is widely publicised on excellent authority.

In order to secure some consistent and reasonable relation between h_c values which can be used for both a $1/2$ " I.P.S pipe and, say, a 55" cast (taken for the moment as a 55" pipe), when both of these are immersed in the "furnace" and absorbing heat from it, the above formula is assumed acceptable for our purposes. It is recognized that there can be never-ending varieties of interpretations and assumptions and rationalized arguments in this matter, but for want of better assumptions we are to proceed from this as a base.

The relative importance of (h_c) , compared with (h_r) , which is a more definite quantity and is applicable to both directions of heat flow, is minor.

For example,

at $T_p = 80^\circ$ and a differential temperature of $600^\circ F = (\Delta T)_p$,

$$h_c = \frac{1.05}{D^{1/4}} + \frac{600}{800} = \frac{1.05}{D^{1/4}} + .75$$

$$h_c \text{ for } 1/2 \text{ I.P.S.} = \frac{1.05}{(1/2)^{1/4}} + .75 = \frac{1.05}{.84} + .75 = 1.25 + .75 = \underline{2.0}$$

$$\text{while } h_r = \underline{4.20} \quad \frac{h_c}{h_r} = \frac{2.0}{4.20} = .476$$

$$\text{and } (h_c + h_r) = 6.20 = \underline{1.475 h_r}$$

$$h_c \text{ for } 55 \text{ pipe} = \frac{1.05}{55^{1/4}} + .75 = \frac{1.05}{2.733} + .75 = .38 + .75 = \underline{1.13}$$

$$h_r = 4.20 \quad \frac{h_c}{h_r} = \frac{1.13}{4.20} = .269$$

$$\text{and } (h_c + h_r) = 5.33 = \underline{1.27 h_r}$$

at $T_p = 80^\circ$ and $(\Delta T)_f = 1200^\circ F$

$$h_c = \frac{1.05}{D^{1/4}} + \frac{1200}{800} = \frac{1.05}{D^{1/4}} + 1.5 \quad (h_c + h_r) = \underline{1.23 h_r}$$

$$h_c \text{ for } 1/2 \text{ I.P.S.} = 1.25 + 1.5 = 2.75$$

$$h_r = 11.85 \quad (h_c + h_r) = 2.75 + 11.85 = 14.60 \text{ (cf } 14.65 \text{ mark)}$$

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Combined convective and radiant heating of a body in a simulated "furnace" situation can be expressed, for our present purposes, as

$$q_p = h_c A_c (T_f - T_p) + h_r A_r (T_f - T_p) \quad \text{where } (T_f - T_p) = (\Delta T)_p$$

where $q_p = \frac{\text{BTU}}{\text{ft.}}$ absorbed by body ($\frac{1}{2}$ " I.P.S pipe)

$$h_c = \frac{BTU}{h \cdot ft^2 \cdot ^\circ F} \quad \text{coef. of convective heating - from furnace to pipe.}$$

$h_2 = \dots$ coef. of radiant " " " " " "
 This coef. combines several factors, including the temp.
 conversion involved by $\frac{T_f^4 - T_p^4}{T_f - T_p}$

A_c = area subjected and responsive to convective cooling or heating. Fins on the cast, and rows on the pipe, make $A_c = A_R$ for the pipe only.

A_2 = area subjected to radiant heating.

$(t_f - t_p)$ = differential temp. between fluid & body (pipe or tank)
mean values for each interval are used.

Expressing the radiant heating effect in this form, once the conversion is made from a T basis to t and h_r values, leads to great convenience in handling and interpreting data of this type, where h_c and h_r phenomena are continuously variable. It has been shown that h_c may be included in an simplified $K h_c$ term, but this is considered more as a checking procedure than an ultra-convenience in calculations - at least at this time.

Since the ultimate purpose of this section is not only to solve the problem of the heating of a specific cask in a standard fire test, but also to provide a possibly improved expression for the thermal conditions of the standard fire test itself, the matter of optimum convenience of any formulation is properly postponed at this time.

5. DATA

5.1 THERMOCOUPLE PIPE DATA

$\frac{1}{2}$ I.P.S. x 1 foot length exposed
 $.622$ " O.D..
 $w = .851$ # weight
 $A = .220$ ft² surface area
 $C_p = .118$ specific heat for mild steel
 $\alpha = .90$ absorptivity (higher mean temp. than for cast)

$(w \cdot C_p) = .851 \times .118 = .1004 \frac{\text{BTU}}{^\circ\text{F}}$

5.2 CASK DATA

49 " - Basic O.D.
 55 " - O.D. over fins (72 fins $\frac{1}{4} \times 3" \times 78\frac{1}{2}"$)
 Outer shell - 1 " carbon steel plate x 8 ft effective thermal height
 Head/shield - 8 " radial
 Inner shell - 30 " I.D. - $\frac{1}{2}$ " S.S. clad carbon steel
 Basket - aluminum - 30 " O.D. x $64\frac{1}{2}"$
 Shape factor $\left(\frac{r_2}{r_1} = \frac{24.5}{15} = 1.63\right) = 1.02$ (Jakob PP-3)
 $\therefore$ wall can be calculated as a plane plate within 2% error.

$\alpha = .80$ absorptivity of surface - gray painted steel - burnt & oxidized
 $\epsilon = .80$ Emissivity of surface (temp cask < temp furnace)

$20,000 \frac{\text{BTU}}{\text{hr}}$ internal heat generated.

Composite value of $(w \cdot C_p) = 3965 \frac{\text{BTU}}{^\circ\text{F}}$	$\frac{\text{BTU}}{^\circ\text{F}}$ after fusion.
$10,000$ # steel @ $C_p = .118 = 1180$	$= 1180$
$6,000$ # aluminum $.24 = 1340$	$= 1340$
$44,000$ # lead $.0328 = 1445$	$= 1628 @ 937$
<u>3965</u>	<u>4148</u>

Addition of $20,000 \frac{\text{BTU}}{\text{hr}}$ during 1-hour test would $= \frac{20,000}{4148} = 4.8^\circ$ rise

Assuming 200° total rise, this supplies only $\frac{1}{14.4}$ part of aluminum heat output. Therefore net remaining to be heated from external furnace source is $\frac{13.4}{14.4} \times 1440 = 1340$, as above.

Therefore in following calculations, no internal heating is assumed.

Heat of fusion for lead at $621^\circ\text{F} = 9.8 \text{ BTU/LB}$ (marks)
 $44,000 \text{ #} \times 9.8 \text{ BTU/LB} = 431,200 \text{ BTU}$ total for all lead.

REFERENCE:

FIRE TEST ANALYSIS

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5.3 Evaluation of A_c and A_n for Cask

assume 8 ft effective height of cask for heat transfer.
Neglect effect of bottom area and of top of closure head.
assume fin area is uniformly distributed over 8 ft height.

$$A_s = \text{area shell without fin base area.} \\ = (8 \text{ ft} \times \frac{\pi 49}{12}) - 72 \left(\frac{78.5}{12} \times \frac{14}{12} \right) = 102.5 - 9.8 = 92.7 \text{ ft}^2$$

$$A_F = \text{area fins} = 72 \left(\frac{78.5}{12} \times \frac{3+3+14}{12} \right) = 245 \text{ ft}^2$$

$$N = W \sqrt{\frac{h}{KY_0}} \quad (\text{Jakob p 235})$$

$$W = \text{fin width} = 3\frac{1}{2} \text{ ft.}$$

$$h = \text{film coef. assumed} = .60$$

$$K = \text{therm. conductivity of fin} = 26 \text{ at } 712^\circ \\ = 22 \text{ @ } 932^\circ$$

$$Y_0 = \text{fin half thickness} \quad \text{assume average} = 24. \\ = \frac{1}{2} \times \frac{14}{12} = .0104 \text{ ft.}$$

$$N = .25 \sqrt{\frac{.60}{24(.0104)}} = .38$$

$$\eta = .95 \text{ from curve} = \tanh(N)$$

$$A_c = A_s + \eta_F A_F = 92.7 + .95(245) = 92.7 + 232.7 \\ = \underline{\underline{325.4 \text{ ft}^2}}$$

$$A_n = \left(\pi \frac{55}{12} \right) \times 8 \text{ ft} = \underline{\underline{115.5 \text{ ft}^2}}$$

since the thermal conductivity of bonded steel and lead is high compared with the heat transfer at the outer surface, it is assumed that the axial conduction of heat in the lead and steel will distribute the peak axial heat absorption internally so that the lead will be of uniform consistency at the end of the heating period of 1 hour.

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E and α
Iron and Steel (not including stainless) (McAdam)

- metallic surfaces or very thin oxide layer
- oxidized surfaces

FIGURE 3

REFERENCE:

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5.5 THERMAL PROPERTIES OF LEAD AND STEEL

$$q = k A \frac{\Delta T}{\Delta x} = \text{BTU/hr}$$

$$1) \text{ Thermal conductivity } k = (\text{BTU/hr/ft}^2/\text{°F}) \left[= \frac{\text{BTU./SQ.FT.}}{\text{hr.} \times \text{°F}} \times \text{ft. thick.} = \frac{\text{BTU/hr.}}{\text{SQ.FT.} \times \text{°F}} \times \text{ft. thick.} \right]$$

ALUM	LEAD	STEEL	TEMP. °F	authority
115	21.		32	Jacob-Hawkins, Elements of Heat Transfer.
114	19		392	" " (from Navy and Am. Steel data)
	9.3		700 (liquid)	" "
	8.9		1000	" "
	8.5		1300	" "
		9.5	212	" " (18-8 Stainless)
		10.2	392	" " " "
		11.0	572	" " " "
		11.7	752	" " " "
		12.5	932	" " " "
	20		32	McAdams - Heat Transmission
	19		212	" (from International Critical Tables)
	18		392	" "
	18		572	" "
	-		621 (melting point)	" "
		26	212	" " mild steel
		26	392	" " "
		25	572	" " "
		23	752	" " "
		22	932	" " "
		21	1112	" " "
		9.4	212	" " AISI 304, 316
		12.4	932	" " " "
	10.5		700 (liquid)	" "
	11.4		900	" " "
			621 (melting point)	" " from "Liquid Metals 1958"
		29.5	212	} Nuclear Engineering - Bonilla
		22.6	932	
	9.2		752	
	8.96		932	
	8.72		1292	" "

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5.6 2) Specific heat c_p $\frac{\text{BTU.}}{(\text{lb})(^\circ\text{F})}$

<u>LEAD</u>	<u>STEEL</u> (mild)	<u>STEEL</u> (304)	<u>AL</u>	<u>TEMP</u> $^\circ\text{F}$
.0306			.2106	32
.0315			.2275	212
.0325			.2344	392
.0335			.2463	572
.0328			.2582	752
.0328			.2702	932
.0328			.2821	1112
.0328			.259	1292

McAdams - Heat Transmission

.038

700 (molten)

McAdams (from liquid - Metal) HB

.037

900

.037

752 (molten)

Nuclear Engineering - Bonelli

.037

932

212

ASME. - Code

.116

.12

.22

.23

212

3) Linear Expansion $\times 10^6 / ^\circ\text{F}$

6.5

8.0

13.1

212

Nuclear Engineering - Bonelli

6.5

9.61

13

13.5

16.2

14.

17.0

6.5

9.3

6.7

13.1

Roark

ALCOA

Eshbach

K.A.P.L

ASME. - Code

4) Thermal Diffusivity α ft^2/hr

.37

$\alpha = \frac{k}{\rho c_p} = \frac{93}{500 \times 0.37} = .43$

Jakob

5) Density ρ lb./ft^3

658

700

Jakob

6) Heat of Fusion BTU/lb

9.8

10.8

Marks p 284
Eshbach 1-125

REFERENCE:

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DETERMINATION OF TIME-TEMP. CURVE FOR "STANDARD" FIRE.

6.1 After the consideration of appropriate values for (h_c) and (α) for the pyrometer tube inserted into the atmosphere of the standard fire, it is possible to estimate the heat received and the temperature of the fire, having given, by specification, the time-temp. curve of the response of the pipe to the fire. The step by step procedure is as follows:

(1) $Q = (w \cdot c_p) \delta T$ (w) and (c_p) are known for the 1/2" I.P.S. pipe 1 ft long. δT is taken from the specified response curve.

(2) $q = \frac{Q}{\delta \theta}$ BTU/hr.
 $H = \frac{Q}{\delta \theta \cdot A}$ BTU/hr ft² $t_0, t_2, t_p, (T_p/100)^4$ are now calculated.

(3) assume a value for ΔT in $\Delta T = t_f - t_p$
 and calculate $t_f, T_f \cdot (T_f/100)^4$

$h_c = \frac{1.05}{D^4} + \frac{\Delta T}{800}$ as previously accepted

$h_r = \frac{\alpha C}{\Delta T} (T_f^4 - T_p^4)$ for the pipe $\alpha = .90$
 $= \frac{.1566}{\Delta T} \left[\left(\frac{T_f}{100} \right)^4 - \left(\frac{T_p}{100} \right)^4 \right]$ $\alpha C T^4 = .1566 \left(\frac{T}{100} \right)^4$ general for T_f and T_p

(4) Substitute in $H = (h_c + h_r) \Delta T$ and check against H in step (2)
 When a check is secured, t_f and T_f are determined correctly and thus provide a point to help identify the desired curve.

6.2

A A

 T_f mean "furnace" temp. °F $(\Delta t)_p$ T_p mean pipe temp. °F ($W.C.P. = .1004$) $(\Delta t)_c$ T_c mean cask temp °F ($W.C.P. = 3965$
OR 4148.) $= 180^\circ\text{F}$ AT START FOR CASK $T_0 = 68^\circ\text{F}$ per Fire Test Spec.

time

HR.

 $= 1/60$ HR. intervals from start to 15 min. $= 1/4$ HR intervals from 15 to 60 min.Nomenclature Q BTU. $g = \frac{Q}{\text{HR.}}$ BTU/HR. $h = \text{coef}$ BTU/HR·FT²·°F $C_p = \text{coef.}$ BTU/lb °F $H = \frac{g}{A}$ BTU/FT²·HR Θ = TIME FROM START, HRS. $\Delta\Theta$ = TIME INCREMENT, HRS. Δt = TEMP. INCREMENT ΔI = TEMP. DIFFERENCE
BETWEEN FURNACE & BODY. $T = ^\circ\text{F}$ $T = ^\circ\text{R}$ SUBSCRIPTS

C CONVECTIVE

R RADIANT $\Rightarrow$

f "FURNACE" (STD. TEST MODEL)

P PIPE (THERMOCOUPLE PROBE)

K CASK (TYPICAL HEAVY BODY)

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6.3

REFERENCE:

STANDARD TIME-TEMPERATURE CURVE
FOR CONTROL OF FIRE TESTS

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Summary Tables of "Pipe" Calculations

Θ	$\delta\Theta$	t_1	t_2	δt	$\overset{\text{mean}}{t_p}$	$\frac{T_p}{100}$	$\left(\frac{T_p}{100}\right)^4$
1	$\frac{1}{60}$	68	340	272	204	6.64	1944.
2	$\frac{1}{60}$	340	564	224	452	9.12	6918.
3	$\frac{1}{60}$	564	744	180	654	11.14	15,400.
4	$\frac{1}{60}$	744	886	142	815	12.75	26,426
5	$\frac{1}{60}$	886	1000	114	943	14.03	38,746.
6	$\frac{1}{60}$	1000	1090	90	1045	15.05	51,303.
7		1090	1162	72	1126	15.86	63,272.
8		1162	1220	58	1191	16.57	74,300
9		1220	1266	46	1243	17.03	84,112.
10		1266	1300	34	1283	17.43	92,297.
11	$\frac{1}{60}$	1300	1327	27	1313.5	17.735	98,929.
12		1327	1349	22	1338.	17.98	104,570
13		1349	1368	19	1358.5	18.185	109,359
14		1368	1385	17	1376.5	18.365	113,753.
15	$\frac{1}{60}$	1385	1400	15	1392.5	18.525	117,770.
16-30	$\frac{1}{4}$	1400	1550	150	1475	19.35	140,192.
31-45	$\frac{1}{4}$	1550	1638	88	1594	20.54	177,992
46-60	$\frac{1}{4}$	1638	1700	62	1669	21.29	205,448

REFERENCE:

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6.5

CONVECTIVE HEATING
OF PIPE.

$$A_c = 220 \text{ ft}^2$$

$$(h_c A_c)(\Delta T \delta \theta)$$

θ	h_c	ΔT	$\Delta T \delta \theta$	Q
1	2.1787	743	12.38	5.935
2	1.877	503	8.38	3.46
3	1.661	329.5	5.49	2.01
4	1.5185	215	3.58	1.19
5	1.431	145	2.42	.76
6	1.375	100	1.66	.505
7	1.337	70	1.16	.344
8	1.315	52	.87	.25
9	1.2968	37.5	.62	.178
10	1.283	26.5	.46	.125
11	1.275	20	.33	.093
12	1.27	16	.26	.075
13	1.266	13	.21	.060
14	1.264	11.5	.19	.053
15	1.2625	10	.16	.046
16-30	1.2575	6	1.50	.415
31-45	1.2537	3	.75	.206
46-60	1.2525	2	.50	.138
			<u>40.92</u>	<u>15.843</u>

BTD.

$$h_{c \text{ mean}} = \frac{Q_{\text{Total}}}{A_c (\sum \Delta T \delta \theta)}$$

$$= \frac{15.843}{(.220)(40.92)} = 1.760_{\text{mean}}$$

$\Delta T \delta \theta$ apply to both h_c and h_2

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6.6

RADIANT HEATING
OF PIPE

θ	h_c	h_r	$(h_c + h_r)$	ΔT	$(h_c + h_r)\Delta T$ H	mean t_f
1	2.1787	7.8499	10.02	743	7449	947
2	1.877	10.327	12.206	503	6137	955
3	1.661	13.31	14.97	329	4932	983.5
4	1.5185	16.649	18.1676	215	3890	1030
5	1.431	20.17	21.60	145	3123	1088
6	1.375	23.577	24.952	100	2466	1145
7	1.337	26.591	27.928	70	1972	1196
8	1.315	29.549	30.864	52	1570	1243
9	1.2968	31.975	33.272	37.5	1260	1280.5
10	1.283	33.937	35.22	26.5	931	1309.5
11	1.275	35.54	36.815	20	740	1333.5
12	1.27	36.898	38.168	16	603	1354
13	1.266	38.065	39.331	13	520	1371.5
14	1.264	39.163	40.427	11.5	466	1388
15	1.2625	40.136	41.399	10	411	1402.5
16-30	1.2575	45.59	46.848	6	274	1481
31-45	1.2537	54.387	55.64	3	160.5	1597
46-60	1.2525	60.526	61.778	2	113.	1671

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6.7

Detail Calculations of "Furnace" Time-Temp. Curve. $\Theta = 1$ First interval of $1/60$ hour. $\delta t = 272^\circ$ from chart of Standard Fire Time-Temp. $t_1 = 68^\circ$ " " $t_2 = t_1 + \delta t = 340^\circ$ t_p as mean value $= t_1 + \frac{\delta t}{2} = 68 + \frac{272}{2} = \underline{204^\circ F}$ $T_p = t_p + 460 = 664^\circ R$ $\left(\frac{T_p}{100}\right)^4 = 6.64^4 = 1944.$ $Q = (w \cdot c_p) \delta t = (.851 \times 118) 272 = .100418 (272) = \underline{27.314 \text{ BTU}}$ $q = \frac{Q}{\delta \Theta} = \frac{27.314}{1/60} = \underline{1638.82 \text{ BTU/HR.}}$ $H = \frac{Q}{\delta \Theta \cdot A} = \frac{27.314}{1/60 \times 220} = \underline{7449 \text{ BTU/HR. FT}^2}$ $\Delta t = t_f - t_p$ $\therefore t_f = \Delta t + t_p$ ~~but~~ $H = (h_c + h_r) \Delta t$ $\therefore \Delta t = \frac{H}{(h_c + h_r)} = \frac{7449}{(h_c + h_r)}$ ~~TRY~~ $\Delta t = 742^\circ$ $t_f = \Delta t + t_p = 742 + 204 = 946^\circ F$ mean furnace temp. $T_f = 946 + 460 = 1406^\circ R$ $\left(\frac{T_f}{100}\right)^4 = (14.06)^4 = 39,078.88$ $h_c = \frac{1.05}{D^{1/4}} + \frac{\Delta t}{800} = \frac{1.05}{(1/2)^{1/4}} + \frac{742}{800} = \frac{1.05}{.84} + 9275 = 1.25 + 9275$
 $= 2.1775$ $h_r = \frac{.1556}{\Delta t} \left(\left(\frac{T_f}{100}\right)^4 - \left(\frac{T_p}{100}\right)^4 \right) = \frac{.1556}{742} \left(\frac{39078.88}{-1944} \right)$
 $= 7.8354$ $(h_c + h_r) = 2.1775 + 7.8354 = 10.0129$ $H = (h_c + h_r) \Delta t = 10.0129 (742) = \underline{7429.57}$ N.G.
 $< 7449.$

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6.7 Cor.

TRY

$$\Delta T = 743^\circ$$

✓

$$T_f = 743 + 204 = 947^\circ F$$

$$T_f = 947 + 460 = 1407^\circ R \quad \left(\frac{T_f}{100}\right)^4 = 14.07^4 = \underline{39190.121}$$

$$h_c = \frac{1.05}{D^W} + \frac{\Delta T}{800} = 1.25 + \frac{743}{800} = 1.25 + .9287 = \underline{2.1787}$$

$$h_2 = \frac{.1566}{743} \left[\frac{39190.121}{-\frac{1994}{37246.121}} \right] = \underline{7.8499}$$

$$(h_c + h_2) = \frac{2.1787}{7.8499} \quad \therefore H = 10.0286 (743) = \underline{7451} \quad \text{OK.} \\ \underline{10.0286} \quad (7449)$$

To shorten calculations, certain quantities can now be most directly calculated in tabular form. These are

t_1 t_2 δT from curve of Standard Fire

$$t_p \text{ mean value} = t_1 + \frac{\delta T}{2}$$

$$T_p \quad \frac{T_p}{100} \quad \left(\frac{T_p}{100}\right)^4$$

$$H = \frac{q}{A \delta \theta} = \frac{(w \cdot c_p) \delta T}{A \delta \theta} = \left(\frac{w \cdot c_p}{A}\right) \frac{\delta T}{\delta \theta} = \left(\frac{100418}{.220}\right) \frac{\delta T}{\delta \theta} \\ = 45644 \frac{\delta T}{\delta \theta}$$

$$\text{For intervals of } \frac{\delta \theta}{\text{only}} = \frac{1}{60} \quad H = 27.3864 \delta T$$

$$\theta = 2 \quad \delta T = 224 \quad t_1 = 340 \quad t_2 = 564 \quad t_p = 452 \quad \left(\frac{T_p}{100}\right)^4 = 6918$$

$$H = 27.3864 (224) = 6137.$$

$$\text{TRY } \Delta T = 503$$

✓

$$T_f = 503 + 452 = 955^\circ F$$

$$T_f = 955 + 460 = 1415^\circ R \quad \left(\frac{T_f}{100}\right)^4 = 14.15^4 = 40,089$$

$$h_c = 1.25 + \frac{503}{800} = 1.25 + .6287 = \underline{1.8787}$$

$$h_2 = \frac{.1566}{503} \left(-\frac{40089}{\frac{6918}{33171}} \right) = \frac{10.3271}{12.2058} = (h_c + h_2)$$

$$H = (h_c + h_2) \Delta T = 12.2058 (503) = 6139.5 \quad \text{OK.} \\ > 6137$$

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6.7 CONT.

$$\Theta = 3 \quad H = 4932 \quad x_p = 654$$

$$\text{TRY } \Delta T = 329.5 \quad x_f = 329.5 + 654 = 983.5$$

$$\checkmark \quad T_f = 983.5 + 460 = 1443.5$$

$$14.435^4 = 43417.7$$

$$h_c = 1.25 + \frac{329.5}{800} = \frac{1.25}{.4118} = \frac{1.6618}{1.6618} = 1.6618$$

$$h_r = \frac{.1566}{329.5} \left(\frac{43417.7}{-15400} \right) = \frac{13.3155}{14.9773} = h_c + h_r$$

$$H = 14.9773 (329.5) = \underline{4935} \quad \text{OK} > 4932$$

$$\Theta = 4 \quad H = 3890$$

$$\text{TRY } \Delta T = 215^\circ$$

$$\checkmark \quad x_f = 215 + 815 = 1030 \quad T_f = 1490^\circ R \quad 14.9^4 = 49,284$$

$$h_c = 1.25 + \frac{215}{800} = \frac{1.25}{.2685} = \frac{1.5185}{1.5185}$$

$$h_r = \frac{.1566}{215} \left[\frac{49284}{-26426} \right] = \frac{16.6491}{18.1676} = h_c + h_r$$

$$H = 18.1676 (215) = \underline{3906} \quad \text{OK} > 3890$$

$$\Theta = 5 \quad H = 3123$$

$$\text{TRY } \Delta T = 145$$

$$\checkmark \quad x_f = 145 + 943 = 1088 \quad T_f = 1548 \quad 15.48^4 = 57,422$$

$$h_c = 1.25 + \frac{145}{800} = \frac{1.25}{.181} = \frac{1.431}{1.431}$$

$$h_r = \frac{.1566}{145} \left(\frac{57,422}{-38,746} \right) = \frac{20.170}{21.601}$$

$$H = 21.601 (145) = 3132 \quad \text{OK} > 3123$$

$$\Theta = 6 \quad H = 2466$$

$$\checkmark \text{TRY } \Delta T = 100 \quad x_f = 100 + 1045 = 1145 = 1605 R$$

$$h_c = 1.25 + \frac{100}{800} = 1.375 \quad 16.05^4 = 66,359$$

$$h_r = \frac{.1566}{100} \left(\frac{66359}{-51303} \right) = \frac{23.577}{24.952} \times 100 = 2495 \quad \text{OK} > 2466$$

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6.7 CONT.

$\Theta = 7 \quad H = 1972$

$\text{TRY } \Delta T = 70 \quad T_f = 70 + 1126 = 1196 = 1656^\circ R$

$\checkmark h_c = 1.25 + \frac{70}{800} = \frac{1.25}{.087} \quad 16.56^4 = \underline{75,204}$

$h_r = \frac{.1566}{70} \left(\frac{75,204}{-63,272} \right) = \frac{26.591}{27.928} \times 70 = \underline{1955} < 1970$
OK.

$\Theta = 8 \quad H = 1590$

$\text{TRY } \Delta T = 52 \quad T_f = 52 + 1191 = 1243 = 1703^\circ R$

$\checkmark h_c = 1.25 + \frac{52}{800} = \frac{1.25}{.065} \quad 17.03^4 = \underline{84,112}$

$h_r = \frac{.1566}{52} \left(\frac{84,112}{-74,300} \right) = \frac{29.549}{30.864} \times 52 = \underline{1604} > 1590$
OK

$\Theta = 9 \quad H = 1260$

$\text{TRY } \Delta T = 37.5 \quad T_f = 37.5 + 1243 = 1280.5 = 1740.5^\circ R$

$\checkmark h_c = 1.25 + \frac{37.5}{800} = \frac{1.25}{.0468} \quad 17.405^4 = \underline{91,769}$

$h_r = \frac{.1566}{37.5} \left(\frac{91,769}{-84,112} \right) = \frac{81.9756}{33.2724} \times 37.5 = \underline{1248} < 1260$
OK

$\Theta = 10 \quad H = 931$

$\text{TRY } \Delta T = 26.5 \quad T_f = 26.5 + 1283 = 1309.5 = 1769.5^\circ R$

$\checkmark h_c = 1.25 + \frac{26.5}{800} = \frac{1.25}{.033} \quad 17.695^4 = \underline{98,040}$

$h_r = \frac{.1566}{26.5} \left(\frac{98,040}{-92,297} \right) = \frac{33.937}{35.220} \times 26.5 = \underline{933} > 931$
OK

$\Theta = 11 \quad H = 740$

$\checkmark \text{TRY } \Delta T = 20 \quad T_f = 20 + 1315.5 = 1333.5 = 1793.5^\circ R$

$h_c = 1.25 + \frac{20}{800} = 1.275 \quad 17.935^4$

$h_r = \frac{.1566}{20} \left(\frac{103,468}{-98,929} \right) = \frac{35.540}{36.815} \times 20 = \underline{736.30} < 740$
OK

$\Theta = 12 \quad H = 603$

$\text{TRY } \Delta T = 16 \quad T_f = 16 + 1338 = 1354 = 1814^\circ R \quad 18.14^4 = 108,280$

$\checkmark h_c = 1.25 + \frac{16}{800} = 1.270$

$h_r = \frac{.1566}{16} \left(\frac{108,280}{-104,570} \right) = \frac{36.898}{38.168} \times 16 = \underline{610.7} > 603$
OK

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6.7 CONT.

$$\Theta = 13 \quad H = 520 \quad T_f = 13 + 1358.5 = 1371.5 = 1831.5 R$$

$$18.315^4 = 112,519$$

TRY $\Delta t = 13$

$$\checkmark h_c = 1.25 + \frac{13}{800} = 1.25 + 0.01625 = 1.266$$

$$h_r = \frac{.1566}{13} \left(\frac{112,519}{-109,359} \right) = \frac{38.065}{39.331} \quad \times 13 = 511.3$$

$$\Theta = 14 \quad H = 466$$

$$OK < 520$$

TRY $\Delta t = 11.5 \quad T_f = 11.5 + 1376.5 = 1388 = 1848 R$

$$18.48^4 = 116,629$$

$$\checkmark h_c = 1.25 + \frac{11.5}{800} = \frac{1.25}{.0143} = 1.2643$$

$$h_r = \frac{.1566}{11.5} \left(\frac{116,629}{-113,753} \right) = \frac{39.163}{40.4273} \quad \times 11.5 = 464.9 \quad OK < 466$$

$$\Theta = 15 \quad H = 411$$

TRY $\Delta t = 10 \quad T_f = 10 + 1392.5 = 1402.5 = 1862.5 R$

$$18.625^4 = 120,333$$

$$\checkmark h_c = 1.25 + \frac{10}{800} = \frac{1.25}{.0125} = 1.2625$$

$$h_r = \frac{.1566}{10} \left(\frac{120,333}{117,770} \right) = \frac{40.1365}{41.3990} \quad \times 10 = 414 \quad OK > 411$$

The remaining intervals are for $\Delta t = 15/60$ hrs. each

$$\Theta = 16-30 \quad H = 274$$

TRY $\Delta t = 6 \quad T_f = 6 + 1475 = 1481 = 1941 R$

$$19.41^4 = 141,939$$

$$\checkmark h_c = 1.25 + \frac{6}{800} = 1.25 + 0.0075 = 1.2575$$

$$h_r = \frac{.1566}{6} \left(\frac{141,939}{140,192} \right) = \frac{45.59}{46.848} \quad \times 6 = 281 \quad OK > 274$$

$$\Theta = 31-45 \quad H = 160.5$$

TRY $\Delta t = 3 \quad T_f = 3 + 1594 = 1597 = 2057 R$

$$20.57^4 = 179,034$$

$$\checkmark h_c = 1.25 + \frac{3}{800} = 1.25 + 0.0037 = 1.2537$$

$$h_r = \frac{.1566}{3} \left(\frac{179,034}{177,992} \right) = \frac{54.3872}{55.6409} \quad \times 3 = 166.9 \quad OK > 160$$

$$\Theta = 46-60 \quad H = 113$$

TRY $\Delta t = 2 \quad T_f = 2 + 1669 = 1671 = 2131 R$

$$21.31^4 = 206,221$$

$$h_c = 1.25 + \frac{2}{800} = 1.2525$$

$$h_r = \frac{.1566}{2} \left(\frac{206,221}{205,448} \right) = \frac{60.5259}{61.7784} \quad \times 2 = 123.5 \quad OK > 113$$

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7 DETERMINATION OF TIME-TEMP. CURVE FOR CASK. (INFINITE CONDUCTIVITY CASE)

7.1 The response of the cask to the same environment that produced the specified response in the pyrometer protection tube (called "pipe") can now be calculated, knowing the temp-temp. curve of the "furnace" itself.

(1) t_f for furnace and
 t_i for cask are known

(2) assume a value for ΔT and determine

t_K , T_K , $(\frac{T_K}{100})^4$ and ΔT_K for the cask.

(3) $h_c = \frac{1.05}{D^{.75}} + \frac{\Delta T}{800}$ (as for the original pipe)

$$h_r = \frac{.1392}{\Delta T} \left[\left(\frac{T_f}{100} \right)^4 - \left(\frac{T_K}{100} \right)^4 \right]$$

$\alpha = .80$ for cask is now included in $\alpha - T^4$ expression.

A_c , A_r and $\Sigma(W.C_p)$ are known
2 values

(4) substitute above quantities in

$$q = (h_c A_c + h_r A_r) \Delta T$$

$$\Delta T = \frac{q \delta \theta}{\Sigma W.C_p} \quad \text{check this value against assumed } \Delta T \text{ value.}$$

(5) final ΔT value allows finding final T_2 value for cask.

(6) If $\Sigma \Delta T$, total temp. rise, brings t to 674°

Calculations are made for an interim interval during which lead melts at constant temperature

$$Q_2 = W_{\text{lead only}} \times 9.8 \text{ Btu/lb}$$

ΔT for this interval is determined in similar manner.

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7.2 DIRECT RADIATION FROM "FURNACE"

The time rate of radiated energy from gray radiator is

$$(1) \quad \dot{q}_g = E_g \sigma A T^4$$

The time rate of radiated energy received by a gray body (cask, etc) is

$$(2) \quad \dot{q} = \alpha_c \sigma A_{rc} T_f^4 \quad \text{where}$$

α_c = absorption coef of body (considered at T_f temp)

A_{rc} = area of body subject to radiation (hereinbefore A_r)

T_f^4 = absolute temp (°R)⁴ of "furnace"

Integration over a 1-hour period gives Q BTU received by body from direct radiation from furnace only (excluding reradiation & convection)

$$(3) \quad Q = \alpha_c A_{rc} [\sum \sigma T_f^4 \times \text{HOURS}] \quad \text{This is found from curve for Furnace time-temp.}$$

TIME	MEAN TEMP °F/100	MEAN ABS. TEMP ($T_f/100$)	($T_f/100$) ⁴	$[\sigma T_f^4 \times \text{HRS.}]$	$[\sum \sigma T_f^4 \times \text{HRS.}]$
0-1	9.47	14.07	39,190.12	113.651	113.651
-2	9.55	14.15	40,089.	116.258	229.909
-3	9.835	14.435	43,417.7	125.911	355.820
-4	10.30	14.90	49,284.	142.923	498.743
-5	10.88	15.48	57,422.	166.523	665.266
-6	11.45	16.05	66,359.	192.441	857.707
-7	11.96	16.56	75,204.	218.091	1075.798
-8	12.43	17.03	84,112.	243.924	1319.722
-9	12.805	17.405	91,769.	266.130	1585.852
-10	13.095	17.695	98,040.	284.316	1870.168
-11	13.335	17.935	103,468.	300.057	2170.225
-12	13.54	18.14	108,280.	314.012	2484.237
-13	13.715	18.315	112,519.	326.305	2810.542
-14	13.88	18.48	116,629.	338.224	3148.766
-15	14.025	18.625	120,333.	348.965	3497.731
15-30	14.81	19.41	141,939.	15 x 411.623 = 6174.35	9672.081
30-45	15.97	20.57	179,034.	15 x 519.198 = 7787.97	17,460.051
45-60	16.71	21.31	206,221.	15 x 598.040 = 8970.60	<u>26,430.651</u>

$$(3A) \quad Q_{\text{BTU}} = \alpha A_r (26,430)$$

This is the direct radiation during the first hour to any body exposed to the "Standard Fire" conditions, implied or specified. This is dominant and basic. Convection and re-radiated energy is referenced to this.

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7.3

"STANDARD"
FIRE

OR

1800

1340°F

1200

740°F

600

140°F

CASK

621°F

0 ABSOLUTE
ZERO

12

24

MINUTES

36

48

60

TIME-TEMP. CURVES FOR FIRE AND CASK.
(INFINITE CONDUCTIVITY) FIGURE 5

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225,000

7.4

200,000

 $(\frac{0.8}{100})^4$

175,000

150,000

125,000

100,000

75,000

50,000

25,000

0

 T^4 - (ABSOLUTE)"STANDARD"
FIRE $(\text{AREA C}) + [\text{AREA A} - \text{AREA B}]$
IS PROPORTIONAL TO $(h_c A_c + h_r A_r)$ (SHOWN GRAPHICALLY IN TERMS OF T^4)
(AND PROPORTIONAL TO ENERGIES INVOLVED)A AREA UNDER "STANDARD" FIRE IS PROPORTIONAL TO
DIRECT RADIATED BTU'S ABSORBED
BY THE CASK.B AREA UNDER "CASK" LINE IS PROPORTIONAL TO
LOSS DUE TO RE-RADIATION FROM CASK.A-B AREA BETWEEN THESE LINES IS PROPORTIONAL
TO $(T_1^4 - T_2^4)$ FOR RADIANT HEATING.C AREA UNDER THIS CURVE PROPORTIONAL TO
CONVECTIVE HEATING.

C + CONVECTIVE HEATING

CASK RE-RADIATION
(621°F)

B

24

MINUTES

36

48

60

 T^4 CURVESFIGURE G

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Summary Tables of Cask Calculations (INFINITE CONDUCTIVITY CASE)

Cask temperatures are now to be determined, step by step, from the time-temp. curve calculated for the "furnace" standard.

Time intervals in this case are different from those taken for the furnace.

θ	$\delta\theta$	mean t_f	$T_f/100$	$(T_f/100)^4$		$C T_f^4 \delta\theta$
1,2	2/60	957	14.11	39,637	$\times \frac{.174}{30} =$	229.895
3,4	2/60	1007	14.67	46,315	"	268.627
5,6	2/60	1116.5	15.765	61,770	"	358.266
7,8,9	3/60	1240.	17.0	83,521	$\times \frac{.174}{20} =$	726.633
10,11,12	3/60	1332.	17.92	103,122	"	897.161
13,14,15	3/60	1387.	18.47	116,377	"	1012.480
16-30	1/4	1481	19.41	141,939	$\times \frac{.174}{4} =$	6174.35
31-41.12	$\frac{11.12}{60}$	1586	20.46	175,235	$\times \frac{.174 \times 11.12}{60} =$	5650.97
41.12 - 48.64	$\frac{7.52}{60}$	1638	20.98	193,741	$\times \frac{.174 \times 7.52}{60} =$	4225.1
48.64 - 60	$\frac{11.36}{60}$	1681	21.41	210,119	$\times \frac{.174 \times 11.36}{60} =$	6922

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7.5 CONT.

Θ	δt	t_2	Δt	$\Delta t \delta \Theta$	$\delta \Theta$
1,2	7.9455	187.9455	767.028	25.5676	$2/60$
3,4	9.1425	197.088	814.4845	27.1494	$2/60$
5,6	11.9045	208.9925	913.462	30.4487	$2/60$
7,8,9	23.4244	232.4169	1018.2775	50.9138	$3/60$
10,11,12	28.1624	260.5793	1085.4831	54.2741	$3/60$
13,14,15	31.0863	291.6656	1110.8707	55.5435	$3/60$
16-30	178.749	470.4146	1100.1344	275.033	$1/4$
31-41.12	150.66	621.07	1040.2854	192.79	$11.12/60$
41.12-48.64	0	621.07	1017.	127.464	$7.52/60$
48.64-60	164.12	785.12	977.95	185.158	$11.36/60$

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θ	h_c	$h_c A_c$	h_r	$h_r A_r$	$(h_c A_c + h_r A_r)$	CONVECTIVE BTU $h_c A_c \cdot \Delta T_{\infty \theta}$	NET RADIANT BTU $h_r A_r \cdot \Delta T_{\infty \theta}$
1,2	1.3442	437.4	6.8813	794.79	1232.9	11,183.22	20,320.87
3,4	1.4036	456.73	7.6058	878.47	1335.2	12,399.99	23,849.93
5,6	1.5273	496.99	9.1184	1053.17	1550.16	15,132.70	32,067.65
7,8,9	1.6583	539.61	11.1221	1284.60	1824.21	27,473.50	65,403.86
10,11,12	1.7423	565.94	12.9045	1490.57	2057.41	30,715.88	80,893.91
13,14,15	1.7741	577.29	14.2149	1641.82	2219.11	32,064.70	91,192.42
16-30	1.7606	572.9	17.327	2001.2	2574.1	157,566.40	550,396.07
31-41.12	1.6858	548.55	22.0792	2550.01	3098.56	<u>105754.95</u> 391,291.34	<u>491,616.42</u> 1,355,741.11
41.12-48.64	1.6567	539.09	24.648	2846.84	3385.93	68,714.56	362,869.61
48.64-60	1.6079	523.2	27.303	3153.5	3676.7	<u>96,874.66</u> 556,880.56	<u>583,895.75</u> 2,302,506.47
						TOTAL CONVECTIVE BTU.	TOTAL NET RADIANT BTU.
						<div style="text-align: center;"> $\underbrace{\hspace{10em}}_0$ 2,859,387.03 TOTAL BTU. RECEIVED @ $\alpha = .80$ </div>	

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7.6

Detail Calculations of Cook Time-Temp. Curve. $\Theta = 1, 2$ $T_f = 951^\circ\text{F}$ mean "furnace" temp. T_1 for cook is started at 180°F TRY $\Delta T = 10^\circ$

$$T_k = \text{mean temp. cook} = 180 + \frac{10}{2} = 185^\circ\text{F} = 645^\circ\text{R}$$

$$\left(\frac{T_c}{100}\right) = 6.45 \quad \left(\frac{T_c}{100}\right)^4 = 6.45^4 = 1730.768$$

$$\Delta T = 951 - 185 = 766^\circ \quad D = 55" \text{ dia} \quad D^4 = 2.7233$$

$$h_c = \frac{1.05}{D^4} + \frac{766}{800} = \frac{1.05}{2.7233} + 9.575 = .3855 + 9.575 = 1.3430$$

$$h_r = \frac{\alpha \sigma}{\Delta T} (T_f^4 - T_{\text{cook}}^4) \quad \alpha = .80 \quad \sigma = .174 \times 10^{-8}$$

$$\therefore h_r = \frac{.1392}{\Delta T} \left[\left(\frac{T_f}{100}\right)^4 - \left(\frac{T_k}{100}\right)^4 \right]$$

$$= \frac{.1392}{766} \left(\frac{39637}{-1730} \right) = 6.8885$$

$$q_c = h_c A_c \Delta T \quad \text{convective rate BTU/HR.}$$

$$= 1.3430 (325.4) 766 = 334,251$$

$$q_r = h_r A_r \Delta T \quad \text{radiant rate BTU/HR.}$$

$$= 6.8885 (115.5) 766 = 609,446$$

$$q = q_c + q_r = 944,197 \text{ BTU/HR.}$$

$$\Delta T = \frac{q}{W.C.P.} = \frac{q}{30 \times 3965} = \frac{944,197}{118,950} = 7.937^\circ \quad \text{N.G. too low } < 10$$

TRY $\Delta T = 7.944$

$$\checkmark T_k = 180 + \frac{7.944}{2} = 183.972^\circ\text{F} = 643.972^\circ\text{R} \quad 6.43972^4 = 1719.$$

$$\Delta T = 951 - 183.972 = 767.028$$

$$h_c = .3855 + \frac{767.028}{800} = \frac{.3855}{1.3442}$$

$$h_r = \frac{.1392}{767.028} \left(\frac{39637}{-1719} \right) = 6.8813$$

$$q = (h_c A_c + h_r A_r) \Delta T$$

$$= [1.3442 (325.4) + 6.8813 (115.5)] \Delta T = (437.4 + 794.79) 767.028$$

$$= 1232.19 (767.028) = 945,124.231$$

$$\Delta T = \frac{q}{30 \times 3965} = \frac{945,124.231}{118,950} = 7.9455^\circ \quad \text{OK}$$

$$T_2 = 180 + \Delta T = 187.9455^\circ$$

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$$\Theta = 3.4 \quad \tau_f = 1007. \quad \tau_{1, \text{calc}} = 187.9455$$

$$\text{TRY } \delta T = 8^\circ \quad \tau_k = \tau_1 + \frac{\delta}{2} = 191.9455 \quad \left(\frac{\tau_k}{100}\right)^4 = 6.5194^4 = 1806.4$$

$$\Delta T = 1007 - 191.9455 = 815.0545$$

$$h_c = .3855 + \frac{815.0545}{800} = \frac{.3855}{1.0188} = 1.4043$$

$$h_2 = \frac{.1392}{815.0545} \left(\frac{46315}{-1806.4} \right) = 7.6014$$

$$\delta T = \left[1.4043 (325.4) + 7.6014 (115.5) \right] \frac{\Delta T}{30 \times 3965}$$

$$= \left[456.95 + 877.96 \right] \frac{815.0545}{118,950} = 9.1469^\circ$$

N.B.
too high

$$\text{TRY } \delta T = 9.14 \quad \tau_c = \tau_1 + \frac{9.14}{2} = 187.9455$$

$$\Delta T = \frac{1007}{-192.5755} = \frac{4.57}{192.5755} \quad \left(\frac{\tau_c}{100}\right)^4 = 6.525155^4 = 1812$$

$$h_c = .3855 + \frac{814.4845}{800} = \frac{.3855}{1.018105} = 1.4036$$

$$h_2 = \frac{.1392}{814.4845} \left(\frac{46315}{1812} \right) = 7.6058$$

$$Q = 91425 \left(\frac{118,950}{30} \right) = 36,250$$

$$\delta T = \left[1.4036 (325.4) + 7.6058 (115.5) \right] \frac{\Delta T}{118,950}$$

$$= (456.73 + 878.47) \frac{814.4845}{118,950}$$

$$= 1335.20 \frac{814.4845}{118,950} = 9.1425^\circ$$

OK

$$\tau_1 = 187.9455$$

$$\tau_2 = 197.0880$$

$$\Theta = 5.6 \quad \tau_f = 1116.5$$

$$\text{TRY } \delta T = 11.9^\circ \quad \tau_k = 197.088 + 5.95 = 203.038$$

$$\Delta T = \frac{1116.5}{-203.038} = \frac{913.462}{913.462}$$

$$h_c = .3855 \frac{1.14183}{1.52733} = \frac{913.462}{800}$$

$$6.63038^4 = 1932.6$$

$$h_2 = \frac{.1392}{913.462} \left(\frac{61770}{1932.6} \right) = 9.1184$$

$$\delta T = \left[1.52733 (325.4) + 9.1184 (115.5) \right] \frac{913.462}{118,950}$$

$$496.99 + 1053.17$$

$$1550.16$$

$$= 1550.16 \times \frac{913.462}{118,950} = 11.9045^\circ \quad \text{OK}$$

$$Q = 47,201$$

$$\tau_2 = \frac{197.088}{11.9045} = 208.9925^\circ$$

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7.6 CONT.

$\Theta = 7, 8, 9$

$T_f = 1240 \quad T_1 = 208.9925$

~~TRY~~ $\delta T = 19$

$T_k = T_1 + 9.5 = 218.4925$

$T_k = 678.4925$

$6.784925^4 = 2119$

$\Delta T = \frac{1240 - 218.4925}{1021.5075}$

$h_c = \frac{.3855}{1.2768} = \frac{1021.5075}{800}$
 1.6623

$h_2 = \frac{.1392}{1021.5075} \left(\frac{83521 - 2119}{81402} \right) = 11.0925$

$\delta T = \left[\frac{1.6623(325.4) + 11.0925(115.5)}{540.91 + 1281.18} \right] \frac{1021.5075}{20 \times 3965}$
 1822.09

$= \frac{1822.09(1021.5075)}{79,300} = 23.471^\circ$

N.G.
 too high

~~TRY~~ $\delta T = 23.46$

$T_k = 208.9925$
 12.73

$\frac{221.7225}{221.7225} \left(\frac{T_k}{100} \right)^4 = 6.817225^4 = 2159.89$

$\Delta T = \frac{1240 - 221.7225}{1018.2775}$

$h_c = \frac{.3855}{1.2728}$
 1.6583

$h_2 = \frac{.1392}{1018.2775} \left(\frac{83521 - 2159.89}{81361.11} \right) = 11.1221$

OK

$\delta T = \left[\frac{1.6583(325.4) + 11.1221(115.5)}{539.61 + 1284.60} \right] \frac{1018.2775}{79300} = 23.4244$
 1824.2

$T_2 = \frac{208.9925 - 23.4244}{232.4169}$

$Q = 92,877$

$\Theta = 10, 11, 12 \quad T_f = 1332$

~~TRY~~ $\delta T = 35^\circ \quad T_k = T_1 + 17.5 = 249.9169$

$7.099169^4 = 2545$

$T_k = 709.9169$

$\Delta T = \frac{1332 - 249.9169}{1082.0831}$

$h_c = \frac{.3855}{1.3526}$
 1.7381

$h_2 = \frac{.1392}{1082.0831} \left[\frac{103,122 - 2545}{100,577} \right] = 12.9383$

N.G.

$\delta T = \left[\frac{1.7381(325.4) + 12.9383(115.5)}{565.57 + 1494.37} \right] \frac{1082.0831}{20 \times 3965} = 28.18$
 2059.94
 too low

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TRY $\delta T = 28.2$

✓

$$T_k = \frac{232.4169}{14.1}$$

$$T_k = \frac{246.5169}{706.5169}$$

$$7.065169^4 = 2491.66$$

$$\Delta t = \frac{1332. - 246.5169}{1085.4831}$$

$$h_c = \frac{.3855}{1.3568} = 1.7423$$

$$h_r = \frac{.1392}{1085.4831} \left[\frac{103122.}{2491.66} \right] = 12.9045$$

OK

$$\delta T = \left[1.7423 (325.4) + 12.9045 (115.5) \right] \frac{1085.4831}{79300} = 28.1624$$

$$\frac{566.94}{1490.47} = 2057.41$$

$$T_2 = \frac{232.4169}{28.1624} = 260.5793$$

$$Q = 111,664$$

$$\Theta = 13, 14, 15$$

$$T_f = 1387.$$

$$\delta \Theta = 1/20 \text{ HR}$$

TRY $\delta T = 33$

$$T_k = \frac{260.5793}{16.5} = 277.0793$$

$$\left(\frac{T_k}{100} \right)^4 = 7.370793^4 = 2951.6$$

$$\Delta t = \frac{1387. - 277.0793}{1109.9207}$$

$$h_c = \frac{.3855}{1.3874} = 1.7729$$

$$h_r = \frac{.1392}{1109.9207} \left[\frac{116,377.}{2951.6} \right] = 14.2252$$

N.B.

$$\delta T = \left[1.7729 (325.4) + 14.2252 (115.5) \right] \frac{1109.9207}{79300} = 31.0708$$

Too low

TRY $\delta T = 31.1$

$$T_k = \frac{260.5293}{15.55} = 276.1293$$

$$\left(\frac{T_k}{100} \right)^4 = 7.361293^4 = 2936.4$$

$$\Delta t = \frac{1387. - 276.1293}{1110.8707}$$

$$h_c = \frac{.3855}{1.3886} = 1.7741$$

$$h_r = \frac{.1392}{1110.8707} \left(\frac{116,377.}{2936.4} \right) = 14.2149$$

$$\delta T = \left[1.7741 (325.4) + 14.2149 (115.5) \right] \frac{1110.8705}{79300} = 31.0863$$

OK

$$\frac{577.29}{1641.82} = 2219.11$$

$$T_1 = 260.5793$$

$$\delta T = 31.0863$$

$$T_2 = 291.6656$$

$$Q = 123,257$$

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7.6 CONT.

$$\Theta = 16-30 \quad \tau_f = 1481 \quad \delta\theta = 1/4 \text{ HR.}$$

$$\text{TRY } \delta t = 193 \quad \tau_k = \left\{ \frac{291.6656}{\frac{91.5}{383.1656}} \right\} \left(\frac{T_k}{100} \right)^4 = 8.431656^4 = \underline{5054.19}$$

$$\Delta t = \frac{1481 - 383.1656}{1097.8344} \quad h_c = \frac{.3855}{\frac{1.3723}{1.7578}}$$

$$h_2 = \frac{.1392}{1097.8344} \left[\frac{141,939}{\frac{5054}{136,885}} \right] = 17.3563 \quad \text{N.G.}$$

$$\delta t = \left[\frac{571.98}{2004.65} + 17.3563(115.5) \right] \frac{1097.8344}{4 \times 3965} = 178.35 \quad \text{too low}$$

$$\text{TRY } \delta t = 178.4 \quad \tau_k = \left\{ \frac{291.6656}{\frac{89.2}{380.8656}} \right\} \left(\frac{T_k}{100} \right)^4 = 8.408656^4 = 4999.27$$

$$\Delta t = \frac{1481 - 380.8656}{1100.1344} \quad h_c = \frac{.3855}{\frac{1.3751}{1.7606}}$$

$$h_2 = \frac{.1392}{1100.1344} \left[\frac{141,939}{\frac{4999}{136,940}} \right] = 17.3270 \quad \text{OK}$$

$$\delta t = \left[\frac{572.9}{2001.2} + 17.327(115.5) \right] \frac{1100.1344}{15860} = 178.749$$

$$\tau_2 = \frac{291.6656}{\frac{178.749}{470.4146}} \quad q = 708,710.$$

$\Theta = 31-41.12$ This interval brings the cook up to 621 °F only

$$\text{TRY } 10 \text{ min interval} \quad \tau_f = 1584 \quad \left(\frac{T_{100}}{100} \right)^4 = 20.44^4 = 174,551.1$$

$$\text{TRY } \delta t = 621 - 470.4 = 150.6$$

$$\tau_k = \frac{470.4146}{\frac{75.3}{545.7146}} \quad \left(\frac{T_k}{100} \right)^4 = 10.057146^4 = 10,230.5$$

$$\Delta t = \frac{1584 - 545.7146}{1038.2854} \quad h_c = \frac{.3855}{\frac{1.2978}{1.6833}}$$

$$h_2 = \frac{.1392}{1038.2854} \left(\frac{174,551.1}{\frac{10,230.5}{164,320.6}} \right) = 22.0313 \quad \text{N.G.}$$

$$\delta t = \left[\frac{547.74}{3092.35} + 22.0313(115.5) \right] \frac{1038.2854}{60\% \times 3965} = 134.961$$

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7.6 Const

TRY 11.12 MIN. Interval (30-41.12 min)

$$T_f = 1584 + 2 = 1586$$

$$\left(\frac{T_f}{100}\right)^4 = 20.46^4 = 175,235.8$$

TRY $\delta T = 150.6$

$$\Delta T = \frac{1586}{-545.7146} = \frac{1040.2854}{1040.2854}$$

$$h_c = \frac{.3855}{1.3003} = \frac{.3855}{1.6858}$$

$$h_2 = \frac{.1392}{1040.2854} \left[\frac{175,235.8}{10,230.5} \right] = 22.0792$$

$$\delta T = \left[\frac{1.6858(325.4)}{548.55} + 22.0792(115.5) \right] \frac{1040.2854}{\frac{60}{11.12} \times 3965} = \frac{150.66}{\frac{2550.01}{3098.56}} \quad \text{OK}$$

$$Q = 597,366.$$

The lead is now beginning to be melted and is absorbing heat at an initial rate of

$$Q = (h_c A_c + h_2 A_2) \Delta T$$

$$= (3098.56)(1040.2854) = 3,223,369.9 \text{ BTU/HR}$$

$$= 53,722. \text{ BTU/MIN.}$$

To melt all the lead will require

$$44,000 \# \times 9.8 \text{ BTU/LB} = 431,200 \text{ BTU}$$

and this will take approx. $\frac{431,200}{53,722} = 8 \text{ min.}$

$$\Theta = 41.12 - 48.64$$

Try an interval of 7.52 min.

$$T_f = 1638$$

$$= 2098^\circ R$$

$$20.98^4 = 193,741$$

$$\checkmark T_k = 621$$

$$= 1081^\circ R$$

$$10.81^4 = 13,655$$

$$\Delta T = 1638 - 621 = 1017$$

$$h_c = \frac{.3855}{1.2712} = \frac{.3855}{1.6567}$$

$$h_2 = \frac{.1392}{1017} \left(\frac{193,741}{-13,655} \right) = 24.648$$

$$Q = \left[\frac{1.6567(325.4)}{539.09} + 24.648(115.5) \right] 1017 = \frac{3,443,490}{2846.84} \text{ BTU/HR}$$

$$= 57,391.5 \text{ BTU/MIN.}$$

$$\frac{431,200}{57,391.5} = 7.52 \text{ min OK}$$

$$\Theta = \frac{41.12}{7.52} = 48.64 \quad \checkmark$$

At the end of this interval, all the lead is melted and the temperature of the whole cast begins to rise again for the remaining 11.36 min. of the hour.

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7.6 CONT.

$$\Theta = 48.64 - 60. \quad T_f = 1681$$

A new (W.C.P) = 4148 is now used for the steel and molten lead.

~~TRY~~ $\delta T = 163.5 \quad T_K = 621 + 81.75 = 702.75 = 1162.75 R$
 $11.6275^4 = 18,278.6$

$$\Delta T = 1681 - 702.75 = 978.25$$

$$h_c = \frac{.3885}{\frac{1.2228}{1.6083}} \quad h_2 = \frac{.1392}{978.25} \left(\frac{210,119.6}{-18,278.6} \right) = 27.298$$

$$q = [1.6083(325.4) + 27.298(115.5)] 978.25 = 3,596,242.$$

$$\begin{array}{r} 523.3 \\ 3152.9 \\ \hline 3676.2 \end{array}$$

$$\delta T = \frac{3,596,242}{4148} \times \frac{11.36}{60} = 164.148$$

Too High.

~~TRY~~ $164.1 \quad T_K = 621 + 82.05 = 703.05$
 $T_K = 1163.05$

$$11.6305^4 = 18,297.4$$

$$\Delta T = 1681 - 703.05 = 977.95$$

$$h_c = \frac{.3855}{\frac{1.2224}{1.6079}} \quad h_2 = \frac{.1392}{977.95} \left(\frac{210,119.6}{-18,297.4} \right) = 27.303$$

$$q = [1.6079(325.4) + 27.303(115.5)] 977.95 = 3,595,628.7$$

$$\begin{array}{r} 523.2 \\ 3153.5 \\ \hline 3676.7 \end{array}$$

$$\delta T = \frac{3,595,628.7}{4148} \times \frac{11.36}{60} = 164.12$$

OK

$$T_2 = 621 + 164.12 = 785.12^\circ F \text{ final temp of cook, (mean)}$$

INFINITE CONDUCTIVITY CASE

$$Q = 680,770.$$

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S. Summary of Temperature Distribution Study.

Considerable time has been expended in the study of various methods of analysis available in the literature of the subject as well as in the development of the most convenient operational calculations for the iterations found necessary.

In general, mathematical methods, except for the basic formulations of heat phenomena, have been found to be inapplicable due to restrictions in the specific conditions. Graphic methods, originally securely based on theory applicable well within the interior of the mass, have been found erroneous for conditions at and near the surface. In fact, certain constructions published by authorities in the field are not only inconsistent among themselves, but are highly misleading quantitatively, particularly at the surface.

Conditions at the surface are dominant and sensitive. Accuracy is vital, both in estimating the ambient conditions to determine the heat input at any interval and in starting the curve of internal distribution. Fine subdivisions in regard to time and dx distances are required for the steel shell analysis.

The array of variable factors which must be accommodated is beyond the abilities of previous graphical methods to present. Mathematical methods would require formulae to be developed, which is a job in itself, and then would require a computer to solve. The iterative method has been found necessary, and has finally been reduced to a reasonable process in spite of the following variables.

1. The ambient temperature varies with time, as developed and shown for reference on pages 20, and 30 -33 of the previous report.
2. The mean temperature of the wall must be found by iteration to correspond with each mean value of the ambient temperature. Unless correspondence is maintained continuously between these two temperatures at each increment of time, the errors become hopeless, due to the effect of the fourth power in radiation calculations.
3. Materials vary across the section, including carbon steel, lead, stainless steel, and aluminum, with changes in several parameters.
4. Thicknesses are unrelated, varying as $1\frac{1}{2}$, 8, $\frac{1}{2}$, and 2.
5. dx subdivisions are necessarily taken at $\frac{1}{4}$, $\frac{1}{2}$ and 1.
6. dθ intervals vary.
7. A datum line at the 621° level distorts the temperature distribution curves as the lead liquifies.
8. Characteristics of the materials change for the higher temperatures.
9. Addition of heat at and through the basket.

The model used in calculations has the identical heat absorption formula and coefficients used for the cask. Its section is, however, that of a uniform cylinder, without the benefit of the metal end masses. The same q rates, modified only for actual cask wall temperatures, are used. The results are conservative, since with nearly the same input heat rates, only about $\frac{3}{4}$ the total mass is involved.

Basket and fuel temperatures are definitely safe. Curves E and F are shown as two iterations starting from two assumed surface final temperatures at the 60 min. time. Curve F exhausted its BTU input. Curve E had 160,000 BTU remaining and undistributed. Curve G represents the final iteration, gives the inner and outer shell temperatures at end of one hour.

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INTRODUCTORY THERMAL EQUATIONS

q = rate of heat flow, to, thru or from a surface.

$$Q_{IN} \text{ or } Q_{OUT} = Q = q \times d\theta = (\text{rate of heat flow}) \times (\text{time})$$

(1) This is steady state flow, without heat storage. (q) is caused by (dt) existing between two planes.

(2) Outside the surface, heat is being received at a rate (q) during a certain interval. Inside the surface, the same rate (q) must exist.

Therefore, without heat storage, a definite ($\frac{dt}{dx}$) is required.

$$K = (\text{BTU/hr} \cdot \text{FT}^2 \cdot ^\circ\text{F}) \times \text{FT}_{\text{thick}}$$

$$KA = (\text{BTU/hr} \cdot ^\circ\text{F}) \times \text{FT}_{\text{thick}}$$

$$\lambda = \frac{q}{KA} = \frac{\text{BTU/hr}}{(\text{BTU/hr} \cdot ^\circ\text{F}) \times \text{FT}_{\text{thick}}} = \frac{^\circ\text{F}}{\text{FT}_{\text{thick}}}$$

$$\text{or } \lambda = \frac{q}{12KA} = \frac{^\circ\text{F}}{\text{INCH}_{\text{thick}}}$$

$$dt = \lambda dx$$

$$q = \frac{Q}{d\theta}$$

$$d\theta = \frac{N_{\text{min}}}{60} \text{ hr}$$

$$= Q \frac{60}{N}$$

$$\frac{1}{d\theta} = \frac{60}{N_{\text{min}}} \text{ hr}^{-1}$$

$$\therefore dt = \left(\frac{q}{12KA} \right) dx$$

$$dt = \frac{Q}{N} \frac{60}{12KA} dx = \frac{5Q}{NKA} dx = \frac{Q}{NKA/5dx}$$

$$Q_{\text{STORED}} = Q_S = (\Delta T)(WC_p) \text{ BTU}$$

$$W = \text{WT. in lbs.}$$

$$Q_F = (\text{BTU/LB})(W)$$

$$\text{BTU HEAT OF FUSION, (A SORT OF "STORAGE")}$$

$$Q_R =$$

$$\text{BTU RADIATED OR CONVECTED AND LOST.}$$

$$Q_{IN} = Q_S + Q_F + Q_{OUT} + Q_L$$

FOR LEAD ONLY

ZERO IN THIS CASE.

FROM JAKOB.

1) Fundamental relation for steady flow of heat by conduction, for a homogeneous substance in which a constant temperature difference ΔT is held between 2 planes of (A) area and (dx) apart. Then a steady heat flow by conduction q_K per unit time occurs.

$$q_K = KA \frac{\Delta T}{dx} \text{ or, as above, } q = KA \frac{dT}{dx} \text{ independent of time for steady state.}$$

2) In addition, in the unsteady state, the rate of heat flow stored has to be considered.

$$q_{ST} = \rho C_p (A \Delta x) \frac{(\Delta T)}{\Delta t} \text{ where } (\Delta T) \text{ means average temp. increase of the substance}$$

$$\therefore Q_{ST} = \rho C_p (A \Delta x) (\Delta T) \text{ is heat stored in volume } (A \Delta x) \text{ in time } (\Delta t)$$

$$\text{in a small volume } (A \Delta x) \text{ in a short time interval } \Delta t$$

The heat flow will decrease only when heat is stored in the substance.

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AT ANY INSTANT, FOR ANY SEGMENT OF ANY TIME CURVE OF TEMPERATURE DISTRIBUTION,

$$q = KA \frac{dT}{dx} \quad \therefore dt = \frac{q_{in} \frac{1}{KA}}{\frac{q_{in}}{12KA}} = \frac{q_{in}}{12KA} \frac{1}{dx}$$

WHERE q IS RATE OF HEAT FLOW THROUGH A PLANE OF AREA A . $Q_{in} = q_{in} dA$

HEAT STORED IN ANY 'SLICE' OF MATERIAL (dx) THICK AND BETWEEN TWO TIME CURVES IS

$$Q_{STORED} = Q_{IN} - Q_{OUT} = \Delta T_S (WCP)$$

$$\Delta T_S = \left(\frac{T_1}{2} + \frac{T_2}{2} \right) - \frac{T_1 + T_2}{2} \quad \text{IN GENERAL}$$

1) FOR EACH $d\theta$ FIND Q_{IN} FOR T_1 AND T_2 AND ΔT

2) FOR EACH 'SLICE' (dx) WITHIN INTERVAL $d\theta$, FIND $dt = \frac{Q_{IN}}{12KA \frac{d\theta}{dx}}$, THEN FIND ($\Delta T_S'$), THEN

$$Q_{STORED} = (\Delta T_S') (WCP), \text{ THEN}$$

$$Q_{OUT} = Q_{IN} - Q_{STORED}$$

3) REPEAT, USING ABOVE Q_{OUT} AS Q_{IN} FOR NEXT 'SLICE'.

CURVE B AT θ_P

NOTE - $\lambda = \frac{dT}{dx}$ IN GENERAL

$\lambda_1 = \frac{dT_1}{dx_1}$ FOR CURVE A WITH CONSTANT INITIAL TEMP (T_0) AND INCREMENT ΔT_A .

$\lambda_1' = \lambda_1 + (\lambda) \Delta T_B$ FOR CURVE B = CURVE A + CURVE B'

IN EACH INSTANCE $(\lambda) \Delta T_B$ ETC IS CALCULATED AS AN INDEPENDENT $\left(\frac{dT}{dx} \right)$ FOR EACH NEW

CURVE A AT θ_A

$\Delta T_B, \Delta T_C$, ETC, GIVING CURVES B', C', ETC.

THEN CURVE B IS OBTAINED BY SUMMATION OF CURVE B' AND A, ETC.

AMBIENT T_f VARIES WITH θ

ALL PARAMETERS SUBJECT TO VARIATIONS AT EACH CHANGE OF dt , dx OR $d\theta$

GENERAL METHOD OF ANALYSIS.

TEMPERATURE DISTRIBUTION
(AT SELECTED INTERVALS)

REFERENCE:

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SECTION VII
Criticality Analysis

Analysis for Piqua Fuel
Reports on Elk River Fuel Reactivity
Report on A/C Analysis of Spiked Elements
Basket Material Specification

REVISED

CRITICALITY ANALYSIS
OF THE
SHIPPING CASK
FOR
PIQUA FUEL

by

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March 22, 1963

For

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Approved

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CRITICALITY ANALYSIS OF THE SHIPPING CASK FOR PIQUA FUEL

I. SUMMARY

The criticality analysis presented here applies to the shipping cask designed for the transport of spent fuel from the first core of the Piqua organic-moderated reactor. This analysis does not consider the shipment of other fuels in this cask, except for other Piqua fuel of the same geometry and composition.

The proposed regulations for criticality safety in the shipment of spent fuel (10 CFR Part 72, see Federal Register, September 23, 1961, and March 5, 1963) would require that the fuel in the cask be less than 75 per cent of a critical mass or that it be shown that for the fully loaded cask, including any fixed poisons, the k_{eff} of the system is no greater than 0.9 under conditions of optimum moderation. The Piqua shipping cask will carry 19 fuel assemblies which is 58 per cent of the experimental critical mass in organic moderator at 325°F. However, it was not demonstrated what mass would be critical under optimum cold moderation conditions. It was, therefore, considered necessary to show by calculation that for the optimum moderation possible in the shipping cask the k_{eff} would not exceed 0.9.

The essential features of the shipping cask and the Piqua fuel assembly are shown in Figure 1. The shipping cask is a cylinder of aluminum surrounded by a lead shield. The aluminum basket is 30 inches in diameter, and 65 inches long. It has an approximately hexagonal array of nineteen holes, each 5.28 inches in diameter, and each designed to hold one Piqua fuel assembly. The Piqua fuel assemblies each contain 81 kg of uranium in a uranium-3.5 per cent molybdenum alloy in the form of two concentric cylinders clad and finned in aluminum. The uranium is enriched to 1.94 ± 0.03 w/o U-235, and hence each fuel assembly contains 1.57 kg U-235. As this fuel is used in the organic-moderated (terphenyl) Piqua reactor, it has a predicted effective multiplication (k_{eff}) of 1.10.

The analysis described herein made use of two nuclear design computer codes, WANDA (1) and PIMG (2) and an IBM-7090 computer. This analysis shows:

1. The cask without special poisons in the aluminum basket meets the requirements of k_{eff} less than 0.9 when loaded with Piqua fuel, and immersed in water.

FIGURE I, PIQUA SHIPPING CASK AND FUEL ASSEMBLY

2. The cask with 1 w/o (weight per cent) cadmium-poisoned aluminum has a k_{∞} under optimally moderated conditions of less than 1.0 and a k_{eff} of less than 0.8 when loaded with Piqua fuel.

3. The method of analysis gives acceptable agreement with a critical experiment on Piqua fuel.

The design criteria of 1 w/o cadmium in the aluminum basket is conservative with regard to meeting Part 72 requirements because the cask will have a k_{eff} of less than 0.8 (required by Part 72: less than 0.9). In addition, the poisoned cask has a k_{∞} of less than 1.0 which implies that the cask is safe from interaction with any number of similar casks, and with any other container which also has a k_{∞} of less than 1.0.

The analysis is considered conservative for two reasons. First, the cadmium content used in the analysis was 0.5 w/o instead of the recommended one per cent cadmium. Second, the more conservative (i.e., the highest k_{eff}) of two parallel nuclear analysis techniques is used as the governing criterion. The least conservative technique used in the analysis gives the best agreement with the critical experiment on the Piqua fuel.

The cadmium in the cask is in no danger of being consumed by neutrons. Even in an inconceivable (for the cask) flux of 10^7 neutrons/cm²sec in the cask, it would take over 1000 years for depletion of one per cent of the high cross section cadmium isotope, Cd-113.

II. THE ANALYSIS

The method of analysis consists of using two nuclear analysis techniques in parallel to obtain two independent calculations of the k_{∞} of the unpoisoned and poisoned unit cells of the cask, and to check each technique against an experiment, the critical experiment on the Piqua fuel. This particular approach assures the detection of any mechanical errors in the preparation of the data, and will give evidence of any systematic errors in the particular method used or in the basic nuclear data. The use of redundant calculations and experimental checkpoints is particularly desirable in criticality evaluations. The two methods used are briefly described below:

Method A:

1. Obtain microscopic thermal cross sections from the SOFOCATE or KATE codes. A compendium of SOFOCATE ⁽³⁾ cross sections was used here. ⁽⁴⁾
2. Obtain microscopic fast group cross sections using the MUFT Code. ⁽⁵⁾ A 3-group set of fast cross sections derived from 54-group MUFT runs was used here. ⁽⁶⁾
3. Obtain the flux shapes and k_{∞} of the unit cell using a 4-group WANDA. ⁽¹⁾

Method B:

1. Obtain microscopic thermal cross sections as in Method A.
2. Obtain the fast group cross sections, the flux shapes and k_{∞} of the unit cell using a 55-group P1MG. ⁽²⁾

In order to obtain the k_{eff} of the cask or the organic critical experiment, a leakage factor is computed using the flux-volume weighted cross sections from the computer runs plus the geometrical bucklings which include reflector savings. In a critical experiment the k_{eff} is, of course, 1.00. Hence a measure of the combined accuracy of the calculational technique and the nuclear data, is how close the predicted k_{eff} of the critical experiment approaches unity. The results below summarize the criticality calculations using each method.

Method A:

	<u>k_{∞}</u>	<u>Leakage</u>	<u>k_{eff}</u>
Unpoisoned Cask	1.02	0.773	0.788
Piqua Critical	1.196	0.834	0.998

Method B:

Unpoisoned Cask	1.066	0.773	0.822
Piqua Critical	1.243	0.834	1.038
Poisoned Cask, (0.5 w/o Cadmium)	0.934	0.773	0.722

Briefly, the Method A results are lower in k_{eff} and give the best prediction of Piqua criticality. The Method B results are systematically higher for a reason discussed later. Notwithstanding this, the Method B results are used, since their use will result in the most conservative (smallest) estimate of the criticality safety margin of the poisoned cask. A more detailed discussion of the procedure and results follows.

Procedure:

1. Obtain the geometry data for the shipping cask and Piqua critical unit cells. Compute the volume fractions within each region, for each material.
2. Obtain the nuclide number densities for the materials in each region of the unit cell. Change these to region-homogenized number densities by multiplying by the appropriate volume fraction.
3. Obtain k_{∞} for each unit cell using both Methods A and B, as described in detail below.
4. Compute k_{eff} using k_{∞} plus computed leakage factors, as described below.
5. Repeat items 3 and 4 to obtain the necessary cask poisoning data, and to obtain the optimally moderated k_{eff} in the poisoned cask.

Table I shows the unit cell geometry data for both the shipping cask and the Piqua critical experiment. The unit cells are conveniently divided into three concentric regions, the inner moderator region, the intermediate fuel region, and the outer region which is aluminum in the shipping cask and organic moderator in the Piqua cell. Table II shows the nuclide concentrations of each material, and the region-homogenized values. The thermal cross-section data which is identical for both Method A and Method B, is shown in Table III. The fast group cross sections and the flux shapes in the unit cells are obtained in two different ways. In Method A, the fast group cross sections are obtained using the 54-group MUFT Code, and the fluxes and k_{∞} are subsequently obtained using the 4-group, one-dimensional WANDA Code. In Method B, the fast cross sections, the thermal and fast fluxes and k_{∞} are all obtained simultaneously using the 54-group PLMG Code.

TABLE I, UNIT CELL DIMENSIONS AND
REGION VOLUME FRACTIONS

<u>Region</u>	<u>Composition</u>	<u>Outer Radius, cm</u>	<u>Volume Fraction of Region</u>
I	H ₂ O (or organic†)	3.890	1.0000
II	304 Stainless	3.915	0.0178
	H ₂ O (or organic)	4.120	0.3448
	1100 Aluminum	4.310	0.2671
	U-3.5 Mo-0.1 Al	4.839	0.3703
	1100 Aluminum	5.029	*
	H ₂ O (or organic)	5.425	*
	1100 Aluminum	5.616	*
	U-3.5 Mo-0.1 Al	6.144	*
	1100 Aluminum	6.335	*
	H ₂ O (or organic)	6.591	*
	347 Stainless	6.617	*
	H ₂ O (or organic)	6.706	*
	Aluminum	8.739	1.0000
III	or		or
	Organic	8.001	1.0000

† Organic (terphenyl) is used in the Piqua unit cell

* Included above

TABLE II, REGION-HOMOGENIZED NUMBER DENSITIES

<u>Region</u>	<u>Material</u>	Unhomogenized <u>$N \cdot D \times 10^{-24}$</u>	<u>Volume Fraction</u>	Homogenized <u>$N \cdot D \times 10^{-24}$</u>
I	H ₂ O		1.0000	
	H	0.06688		0.06688
	O	0.03344		0.03344
	or Organic		1.0000	
	H	0.0336		0.0336
	C	0.044		0.044
II	H ₂ O		0.3448	
	H	0.06688		0.02306
	O	0.03344		0.01153
	or Organic		0.3448	
	H	0.0336		0.01159
	C	0.044		0.01517
	SS		0.0178	
	Fe	0.06517		0.001161
	Cr	0.01585		0.000282
	Ni	0.00705		0.000126
	Al	0.0598	0.2671	0.01612
	Fuel		0.3703	
	U-235	0.0008674		0.0003212
	U-238	0.04355		0.01613
	Mo	0.004039		0.001496
III	Al	0.0598	1.0000	0.0598
	or Organic		1.0000	
	H	0.0336		0.0336
	C	0.044		0.044

TABLE III, THERMAL CROSS SECTION DATA

A. MICROSCOPIC DATA - Cross Sections in Barns

Nuclide	CASK AT 20°C		CRITICAL AT 350°F	
	Absorption	Transport	Absorption	Transport
H	0.294	32	0.238	26
O	--	4.0	--	--
C	--	--	0.0033	4.4
Mo	2.22	9.2	1.62	8.6
Fe	2.24	11.3	1.81	13.1
Ni	4.26	21.8	3.44	20.9
Al	0.227	1.6	0.183	1.6
Cr	2.75	7.0	2.22	6.4
Cd	2980	2990	--	--
U-235	603	613	472	482
U-238	2.42	11.9	1.95	11.5
U-235 Nu-fission		1237		970

B. MACROSCOPIC DATA - Cross Sections in cm^{-1}

Region	Shipping Cask			Pigua Critical	
	I	II	III	I & III	II
Σ_a	0.01967	0.2504	0.01357	0.00884	0.1982
Σ_{tr}	2.274	1.230	0.0957	1.1562	0.7623
$\nu\Sigma_f$	0	0.3973	0	0	0.3048
D (cm)	0.1466	0.2710	3.483	0.2883	0.4373

Method A:

Fast group cross sections were obtained from a tabulation ⁽⁶⁾ of effective 3-group constants computed by the 54-group MUFT Code. This tabulation applies to water reactors, and is based on an L-factor of 0.9. This L-factor is defined as the ratio of the heterogeneous to the homogeneous resonance integral of U-238, and is a necessary input to both the MUFT and the PLMG Codes. Since it affects the resonance escape probability, it also influences the computed k_{∞} of the system.

Table IV shows the removal, absorption, and nu-fission cross sections, plus the diffusion constant for the three fast energy groups. These are obtained from the MUFT tabulation and are required, along with the thermal cross sections for the 4-group WANDA calculation.

The results of the two runs are:

	k_{∞}
Shipping Cask	1.020
Piqua Critical	1.198

A preliminary cask poisoning study was performed by simply adding a thermal poison macroscopic cross section to the third (aluminum) region of the shipping cask cell, with the following results:

		k_{∞}
Shipping Cask, unpoisoned	+ 0cm ⁻¹	1.020
Shipping Cask	+ 0.05cm ⁻¹	0.938
Shipping Cask	+ 0.10cm ⁻¹	0.895
Shipping Cask	+ 0.20cm ⁻¹	0.855
Shipping Cask	+ 0.50cm ⁻¹	0.828

TABLE IV, FAST GROUP MACROSCOPIC
CROSS SECTIONS

SHIPPING CASK UNIT CELL

Region	Group	D	Σ_r	Σ_a	$\nu\Sigma_f$
I	1	2.118	.1091	.00113	0
	2	1.004	.1509	.000012	0
	3	0.5871	.1404	.00076	0
II	1	1.813	.08205	.00858	.01907
	2	1.144	.05626	.00599	.00154
	3	0.8804	.04861	.05387	.02231
III	1	2.753	0.01997	.00053	
	2	3.381	.00328	.00021	
	3	4.547	.00060	.00156	

PIQUA UNIT CELL

I and III	1	3.432	.06002	0	0
	2	1.319	.07955	0	0
	3	0.7712	.07368	.000383	0
II	1	2.044	.06514	.00819	.01907
	2	1.242	.03165	.00599	.00154
	3	1.005	.02560	.05400	.02231

These macroscopic thermal cross sections can be represented by the following weight per cents of various poison materials.

<u>Thermal</u> <u>Cross Section</u>	<u>Weight Per Cent of:</u>		
	<u>Dysprosium</u>	<u>Cadmium</u>	<u>Gadolinium</u>
0.05	0.51	0.12	0.014
0.10	1.02	0.23	0.027
0.20	2.02	0.47	0.054
0.50	4.91	1.16	0.13

On the basis of the above, plus the fact that Cadmium is soluble in aluminum up to about 1 w/o, an initial recommendation was made to incorporate a cadmium poison into the aluminum cask.

Method B:

The PLMG Code computes the fast group cross section, the fast and thermal fluxes and the k_{∞} of the system, and requires number densities and thermal cross sections as input data. It also requires an L-factor defined previously. Since the homogeneous resonance integral of U-238 is always larger than the heterogeneous, the L-factor will be less than unity. In criticality calculations, it is therefore conservative to assume an L-factor of unity, as was done in this work.

In addition to the PLMG runs on the Piqua critical and the shipping cask, the PLMG Code was used to analyse the shipping cask with 0.5 w/o cadmium poison in the aluminum, and also to evaluate the effect of water density changes. These results are shown below:

	<u>Water Density</u>	<u>k_{∞}</u>
Piqua Critical	---	1.243
Shipping Cask, no poison	1.0	1.066
Shipping Cask, +0.5 w/o Cd	1.0	0.932
Shipping Cask, +0.5 w/o Cd	0.9	0.945
Shipping Cask, +0.5 w/o Cd	0.7	0.960
Shipping Cask, +0.5 w/o Cd	0.4	0.932

The above results give a consistently higher k_{eff} than do the MUFT-WANDA calculations, the reason being the underestimate of resonance absorptions in the PIMG calculations, due to the assumption of a unit L-factor. It should also be noted that the optimum moderation of the infinite system occurs at a water density of about 0.7, but that a gain of less than 0.03 in k_{∞} occurs.

In the library of basic nuclear data used by the PIMG code during calculations, there is no resonance cross section data for cadmium. Hence Boron-10 data, which is in the code library, was used as a pseudo-cadmium poison. The number density of B-10, N_{B10} , which gives equivalent resonance absorption to a given amount of Cadmium, N_{Cd} , is given by:

$$N_{\text{B10}} = \frac{(\text{RI})_{\text{Cd}}}{(\text{RI})_{\text{B10}}} N_{\text{Cd}}$$

where the RI's are the resonance integrals of the respective isotopes. Numerically:

$$\frac{N_{\text{B10}}}{N_{\text{Cd}}} = \frac{(\text{RI})_{\text{Cd}}}{(\text{RI})_{\text{B10}}} = \frac{92}{1880} = 0.049$$

In this work, in order to underestimate, if anything, the resonance absorptions of the poison, a ratio of 0.04 was used. In the thermal region, actual Cadmium cross sections were employed.

The Computation of Leakage and k_{eff}

The effective multiplication factor, k_{eff} , is obtained by multiplying the computed k_{∞} by a leakage factor, ℓ , computed from Fermi Age Theory.

$$k_{\text{eff}} = \ell \cdot k_{\infty}$$

$$\ell = e^{-B^2 M^2}$$

where B^2 is the geometrical buckling, and

M^2 is the migration area

$$B^2 = \left(\frac{2.405}{R + \delta} \right)^2 + \left(\frac{\pi}{H + 2\delta} \right)^2$$

$$M^2 = \sum_{i=1,4} \frac{D_i}{\Sigma_i}$$

summation over four groups

R is the radius of the system in cm

H is the height in cm

δ is the reflector savings

Table V, following, is a tabulation of the data which make up the leakage factors, and includes a summary of the final results.

Referring to part C of Table V, the k_{eff} of the critical experiment is 1.00, by definition. The prediction using Method A is closer to this value. However, Method B overpredicts the reactivity of the system and hence errs in the conservative direction, which is desirable for criticality analyses. The values obtained using Method B are therefore chosen as the governing criteria.

One additional factor to be considered in the analysis is the uncertainty due to uncertainty in the fuel enrichment. In the Piqua fuel, an uncertainty of ± 0.1 w/o in enrichment creates an uncertainty of $\pm 0.02 \Delta k$. The stated uncertainty of ± 0.03 w/o in the Piqua fuel enrichment results in an uncertainty of $\pm 0.006 \Delta k$; which is of little concern in this analysis.

TABLE V, COMPUTATION OF LEAKAGE FACTORS

A. GROUP-BY-GROUP MIGRATION AREAS

<u>Group</u>	1	2	3	4	Total $M^2 \text{cm}^{-2}$
Piqua Critical	39.4	20.5	11.1	7.2	78.2
Cask, Unpoisoned	32.8	29.6	15.1	2.9	80.4
Cask, Poisoned, Opt. Mod.	52.0	55.1	24.4	2.9	134.4

B. LEAKAGE FACTORS

	R	H	δ	B^2	$\ell = e^{-B^2 M^2}$
Piqua Critical	46.0	137	9	.00232	0.834
Cask, Unpoisoned	38.1	137	7.5	.00322	0.773
Cask, Poisoned, Opt. Mod.	38.1	137	10	.00289	0.678

C. FINAL SUMMARY

	<u>Method</u>	<u>k_{∞}</u>	<u>ℓ</u>	<u>k_{eff}</u>
Piqua Critical	A	1.198	0.834	0.998
	B	1.243	0.834	1.037
Cask, Unpoisoned	A	1.020	0.773	0.788
	B	1.066	0.773	0.824
Cask, Poisoned	B	0.934	0.773	0.722
Cask, Poisoned Opt. Mod.	B	0.960	0.678	0.651

III. BIBLIOGRAPHY

1. WANDA - A One-Dimensional Few-Group Diffusion Equation Code for the IBM-704. WAPD-TM-28, Addendum 2.
2. PLMG - A One-Dimensional Multigroup P1 Code for the IBM-704. WAPD-TM-135.
3. The Calculation of Thermal Constants Averaged Over a Wigner-Wilkins Flux Spectrum; SOFOCATE. WAPD-TM-39.
4. Cross Sections in the SOFOCATE Code, Section Deck. WAPD-TM-72.
5. MUFT-4, Fast Neutron Spectrum Code for the IBM-704. WAPD-TM-67.
6. Effective Fast Group Cross Sections. H_2O Moderated Reactors. WCAP-1511.

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ALLIS-CHALMERS MANUFACTURING COMPANY
508 Kennedy Street, N.W. Brightwood Station, P.O.Box No.8697

Nuclear Power Department
Atomic Energy Division

Cable Address
Founders - Washington

March 20, 1963

Mr. James P. Lagoski
Reactor Engineering Division
U. S. Atomic Energy Commission
9800 South Cass Avenue
Argonne, Illinois

Dear Mr. Lagowski:

In your recent conversation with Mr. Fisher and me, you asked for estimates of the number of Elk River elements needed to achieve criticality. These estimates are contained in the enclosed memorandum from Mr. Fisher.

Sincerely yours,

(Signed) J. H. Blachly

Joseph H. Blachly
Manager of Projects

dbb

Enclosure:
as indicated

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ALLIS-CHALMERS MANUFACTURING COMPANY
INTER - OFFICE CORRESPONDENCE

To: J. H. Blachly

From: J. R. Fisher

Attention:

Date: March 18, 1963

Refer to:

Subject: ERR Fuel Elements

Cust.P.O.#

C.O. Reg.#

S.O.#

In answer to your request we have estimated the minimum number of Elk River fuel elements to achieve criticality. The number of regular elements was obtained from the measurements and the number of spiked elements extrapolated from the measurements.

Number of regular elements----- 30

Number of spiked elements----- 20

(Signed) J. R. Fisher

J. R. Fisher
Core Physics & Shielding

JRF:cha

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March 26, 1963

MR JAMES P LAGOWSKI
REACTOR ENGINEERING DIVISION
CHICAGO OPERATIONS OFFICE

RE MY LETTER DATED MARCH 20 AND THE ENCLOSED MEMORANDUM FROM
JACK FISHER DATED MARCH 18, THE ESTIMATED MINIMUM NUMBER OF ELK
RIVER FUEL ELEMENTS TO ACHIEVE CRITICALITY WAS BASED ON THE CLEAN
COLD CONDITION.

J H BLACHLY
ALLIS CHALMERS MFG CO
WASHINGTON D C

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(COPY FROM ACNP 62533)

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2.3 CRITICALITY

The cask meets the criticality requirements of Sec. 72.37 of the proposed AEC regulation.

The criticality analysis was based upon four assumptions:

- (1) that all elements contain fuel enriched to 5.2 per cent in uranium-235;
- (2) that all elements are unirradiated (i.e., that, for the ERR elements, reactivity is at its maximum);
- (3) that the holes in which the elements are inserted are filled with water; and
- (4) that the aluminum of the casting may be considered as a neutron poison.

Two-group, two-region diffusion theory yields an effective multiplication factor of 0.88 for a single cask. This result meets the requirement of Sec. 72.37 of the proposed regulation, which states that either an effective multiplication factor of 0.9 or 75 per cent of the number of elements forming a critical mass is to be the limit.

KNAPP MILLS INC
WILMINGTON DELAWARE

PIQUA-ELK RIVER SPENT
FUEL SHIPPING CASK

PIQUA-ELK RIVER REACTORS
SPENT FUEL SHIPPING CASK

MATERIAL SPECIFICATION MS-3100-1

FUEL ASSEMBLY BASKET

Revision 1

REVISED

ORIGINATOR RWP APPROVED _____ DATE Jan. 3, 1963 PAGE _____ OF _____

I. Scope

This specification covers the requirements for an aluminum alloy billet from which the Piqua-Elk River Reactors spent fuel shipping cask fuel basket will be machined.

II. Material Specification

- a. The billet shall be forged of commercial 6061 aluminum ingot with a nominal one weight percent addition of Cadmium included in the basic alloy to obtain a uniform distribution of the Cadmium throughout the forged billet. The forged billet shall be delivered in the "O" (annealed) condition.
- b. The forged billet shall be free from voids, cracks, porosity or slag inclusions which would be visible to the naked eye after machining the external surfaces and boring the fuel cavities in the billet.
- c. The distribution of Cadmium in the billet shall be as uniform as possible and in no case shall any one ounce sample taken from any location in the billet contain less than 0.5 weight percent Cadmium.

III. Billet Dimensions

The forged billet as delivered shall be of such size to allow finish machining to 30 inches in diameter by 66 inches long allowing for surface irregularities and sufficient stock removal to get down to sound base metal. It is the billet suppliers responsibility to establish billet dimensions. However, in no case shall the dimensions of the billet if delivered rough machined be less than 30-3/8 inches in diameter by 66-3/8 inches long.

IV. Acceptance Tests

- a. Chemical and physical tests on the delivered billet normal to commercial work are required to assure compliance with the basic 6061-0 material specification. The aluminum content of the material may be one weight percent lower than the minimum specified for alloy 6061 to allow for the Cadmium addition. Notarized chemical and physical test reports shall be delivered with the billet.
- b. During machining Knapp Mills will collect approximately 100 samples of chips from various locations in the billet. The chips collected will be reduced to one ounce samples and analyzed by an independent laboratory for Cadmium content. All samples must comply with Section II-c of this specification.

REVISED 1/3/63

PIQUA-ELK RIVER SPENT
FUEL SHIPPING CASK

c. It is recommended, but not mandatory, that the billet supplier analyze samples taken from the billet external surfaces for Cadmium content and distribution prior to delivery of the billet.

REVISED	Rev	1						
		1/3/63						

SECTION VIII
MISCELANEOUS CALCULATIONS

Iodine Inventory in Cask
Fuel Pin Internal Pressure-ERR
Lead Expansion-Normal Conditions

REVISED

Calculation of Iodine Inventory of Loaded Piqua-Elk River Spent Fuel Shipping Cask

A. Half-Life of Iodines⁽¹⁾

		Reduction Factor for 120 Days Decay Time
I-131	8.1 days	$2. \times 10^{-5}$
I-132	2.4 hours	10^{-30}
I-133	20.5 hours	10^{-42}
I-134	12.5 minutes	10^{-960}
I-135	6.7 hours	10^{-130}

B. Calculation of Iodine Inventory

1. Assumptions:

- 120 days cooling time for fuel
- 53 Mw operation for Elk River;⁽²⁾ 45. Mw operation for Piqua⁽³⁾
- 1.5 peak to average flux ratio for Elk River;⁽²⁾ 1.3 for Piqua⁽³⁾
- 143 fuel elements for Elk River;⁽²⁾ 85 for Piqua⁽³⁾
- 19 of hottest fuel elements per cask
- I-131 is only isotope of interest after 120 days.
- 33% maximum iodine release from fuel element⁽⁷⁾

2. Iodine Inventory in Core (Elk River)

- Approximately 25,000 curies of I-131 per Mw at equilibrium⁽⁴⁾ ⁽⁵⁾
- $25,000 \text{ curies/megawatt} \times 53 \text{ megawatts} = 1.33 \times 10^6 \text{ curies}$
- $1.33 \times 10^6 \text{ curies} \times 2.5 \times 10^{-5} = 33.3 \text{ curies after 120 days}$
- $33.3 \text{ curies} \div 143 \text{ elements} = 0.233 \text{ curies per element (average)}$
- $0.233 \text{ curies} \times 1.5 = 0.35 \text{ curies per element (maximum)}$

3. Iodine Inventory in Core (Piqua)

- $25,000 \times 45.5 = 1.14 \times 10^6 \text{ curies}$
- $1.14 \times 10^6 \times 2.5 \times 10^{-5} = 28.6 \text{ curies}$
- $28.6 \div 85 = 0.336 \text{ curies/element (average)}$
- $0.336 \times 1.3 = 0.44 \text{ curies/element (maximum)}$

4. Iodine Inventory in Cask

- a. $0.44 \times 19 = 8.4$ curies (Elk River)
- b. $0.64 \times 19 = 12.1$ curies (Piqua)

5. Maximum Iodine Release⁽⁷⁾

- a. $8.4 \text{ curies} \times 0.33 = 2.8 \text{ curies (maximum release) (Elk River)}$
- b. $12.1 \text{ curies} \times 0.33 = 4.0 \text{ curies (maximum release) (Piqua)}$
- c. These amounts are less than those allowed by Section 72.34-(o).

6. External Radiation Levels

- a. Gamma dose rate for I-131 is 0.225 rads per curie (6)
- b. Elk River: $8.4 \text{ curies (iodine inventory in cask)} \times 0.33$
 $(\text{maximum release}) \times 0.225 \text{ (rads per hour per curie at one meter)} = 0.62 \text{ rad/hr}$
- c. Piqua: $12.1 \text{ curies} \times 0.33 \times 0.225 = 0.90 \text{ rad/hr}$
- d. Even if the available iodine were released, the resultant levels would be below those allowed in Section 72.34-(n).

References:

- (1) Nuclear Engineering Handbook, Etherington
- (2) Elk River Reactor Hazards Summary Report, with addenda
- (3) Piqua Reactor Hazards Summary Report, with addenda
- (4) KAPL-1178, Graphic Aids to Estimate Nuclear Radiation Hazards, J. J. Fitzgerald, et al, Page 19
- (5) PB 121734R, Radiological Health Handbook, Page 97
- (6) Safe Handling of Radioisotopes, Safety Series No. 2, IAEA, Page 26
- (7) ORNL-CP-57-6-87, Parker and Creek

C O P Y
ALLIS-CHALMERS MANUFACTURING COMPANY
508 Kennedy Street, N.W. Brightwood Station P.O. Box No. 8697
Washington 11, D. C.
Tel. TUCKERMAN 2-9650

September 8, 1961

Mr. R. W. Peterson
Knapp Mills, Incorporated
Foot of West Street
Wilmington, Delaware

Subject: Fuel Transfer Cask

Dear Mr. Peterson:

Enclosed are copies of materials regarding the fuel transfer cask which you requested while visiting at the site.

The 12E11005, 007, 011, and 042 drawings are Sargent & Lundy's which we have requested, and they will be forwarded to you.

You will note that a copy of the fission gas release rate as determined by General Electric from the fuel irradiation program is not included. The reason is that the results of the first half of the capsule irradiated program yielded data that was not conclusive because vacuum measuring equipment was inadequate to obtain accurate results. However, calculations were performed by Allis-Chalmers using 10% fission gas release which is conservative based on many irradiation studies of fuel pellets which provide a gas release between 3% and 8%. The results of this analysis are listed below:

1. Maximum lb-moles of He loaded in fuel tube =
 0.7805×10^{-6} .
2. Partial pressure of He at reactor operating temperature at end of 10,000 Mwd/MT. = 67 psia.
3. Gram-moles of fission gas released to fission gas space in fuel rod at end of 10,000 Mwd/MT = 1196×10^{-6} .

Mr. R. W. Peterson

- 2 -

4. Partial pressure in average tube at end of 10,000 Mwd/MT = 225 psia.
5. Sum of partial pressures, He plus fission gases = 292 psi.

If any additional information is needed, please let us know.

Sincerely yours,

ALLIS-CHALMERS MANUFACTURING COMPANY

Joseph H. Blachly
Project Manager, Elk River Reactor

JHB/RCS/raw
Enclosures

1.- LEAD EXPANSION - CASE BODY AND CLOSURE HEAD

AS THE OPERATING TEMPERATURE OF THE CASE IS REACHED, THE LEAD SHIELDING WILL EXPAND. A VOID IS PROVIDED IN THE LEAD SHIELD WHICH WILL ACCOMMODATE THE LEAD EXPANSION. THE VOLUME OF THE VOID MUST BE SUFFICIENT TO RECEIVE THE INCREASE IN LEAD VOLUME YET WILL NOT ALLOW THE EXPANDING LEAD TO COMPRESS THE AIR, WHICH IS PRESENT IN THE ORIGINAL VOID, TO A DEGREE THAT WOULD CREATE EXCESSIVE PRESSURE ON THE STEEL WALLS. THE FOLLOWING FOUR AREAS WILL BE INVESTIGATED TO DETERMINE THIS SIZE AND LOCATION OF THE EXPANSION VOID.

1.1) DETERMINE THE SAFE WORKING PRESSURE THAT THE STEEL WALLS OF THE CASE AND CLOSURE HEAD CAN WITHSTAND. THE YIELD STRENGTH OF THE MATERIALS INVOLVED SHALL BE USED AS THE DESIGN STRESS.

1.2) DETERMINE THE INCREASE IN LEAD VOLUME DUE TO THE RISE IN TEMPERATURE FROM AMBIENT TO OPERATING

a) FROM THE THERMAL ANALYSIS IT WAS DETERMINED THAT UNDER NORMAL OPERATING CONDITIONS THE AVERAGE TEMPERATURE OF THE LEAD SHIELDING WILL BE 158°F IN THE CLOSURE HEAD AND 200°F IN THE CASE BODY.

REVISED

1.- LEAD EXPANSION - CONTINUED

b) COEFFICIENT OF EXPANSION -

$16.3 \times 10^{-6} / ^\circ F$, LEAD, LINEAR

$6.7 \times 10^{-6} / ^\circ F$, STEEL, LINEAR

$9.6 \times 10^{-6} / ^\circ F$, DIFFERENTIAL (LEAD & STEEL)

$\times 3$

$28.8 \times 10^{-6} / ^\circ F$, DIFFERENTIAL, CUBICAL

1.3) DETERMINE THE VOLUME OF THE EXPANSION VOID REQUIRED TO ACCOMMODATE THE INCREASE IN LEAD VOLUME AND THE ACCOMPANYING DECREASE IN AIR VOLUME TO A DEGREE WHICH WILL NOT DEVELOP A PRESSURE GREATER THAN THAT CALCULATED IN PART 1

1.4) DIMENSION AND LOCATE VOID IN THE CASK BODY AND CLOSURE HEAD. RELATIVE TO DIMENSION AND LOCATION OF THE VOID A CHECK OF SHIELDING ADEQUACY MUST BE MADE.

2- SAFE WORKING PRESSURE CALCULATION

CLOSURE HEAD

THESE A & B
POINTS WILL BE
ANALYZED SINCE
THEY ARE THE VIEWED
POINTS OF THE
HEAD.

POINT A CALCULATIONS - USING AISC WELD FORMULA

$$F = \frac{t^2 S}{2.16}$$

$$t = 0.625$$

$$S = 20000 \text{ PSI}$$

$$C = 0.625$$

$$d = 20.5$$

$$P = \frac{(0.625)^2 (20000)}{2.16 (20.5)^2}$$

$$P = \frac{11710}{105} = 111.5 \text{ PSI / 112 PSI}$$

POINT B CALCULATIONS -

$$w = \frac{2W}{4\pi a^2}$$

$$W = \frac{S_r 4 t^2}{3}, \quad W = w \pi a^2$$

$$w = \frac{S_r 4 t^2}{3 a^2}$$

$$S_r = 20000 \text{ PSI}$$

$$t = 1$$

$$a = 24.25$$

$$w = \frac{S_r 4 t^2}{3 a^2} = \frac{(20000)(4)(1)^2}{3 (24.25)^2} = \frac{12000}{1765} = 6.8 \text{ PSI}$$

REVISED

2- SAFE WORKING PRESSURE CALCULATION - CONT.
CASK BODY CALCULATIONS.

By inspection it can be seen that the weakest members of the cask structure are the flat plates marked "A", "B", "C". Safe working pressure for the cask body will be determined from the calculation of these three plates.

PL "A" CALCULATION - USING ASME CODE FORMULA

$$P = \frac{t^3 S}{C d^2}$$

$$\begin{aligned} t &= 1.25 \\ S &= 30000 \\ C &= 0.25 \\ d &= 47 \end{aligned}$$

$$P = \frac{(1.563)(30000)}{(0.25)(2209)} = \frac{46900}{552} = \underline{85 \text{ psi}}$$

PL "B" CALCULATIONS - USING ASME CODE FORMULA

$$P = \frac{t^3 S}{C d^2}$$

$$\begin{aligned} t &= 1 \\ S &= 30000 \\ C &= 0.25 \\ d &= 49 \end{aligned}$$

$$P = \frac{(1)(30000)}{(0.25)(841)} = \frac{30000}{210} = \underline{142.8 \text{ psi}}$$

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2-SAFE WORKING PRESSURE CALCULATIONS - CONT.

"C" CALCULATION -

REF. R.J. KOEHL
CASE 17

"W" WILL BE TAKEN AS
85 PSI WHICH UP TO
THIS POINT IS THE
LIMITING PRESSURE.

CALCULATION WILL BE
MADE TO DETERMINE THE
STRESS DEVELOPED BY
THE 85 PSI LOADING.

$$\text{Max. } S = \frac{\beta w a^2}{l^2}$$

$$S = \frac{(0.259)(85)(24.5^2)}{(1.125^2)}$$

$$S = 10450 \text{ psi}$$

STRESS COEFFICIENT β

$$a/b = 24.5 / 15.5 = 1.58$$

FROM TABLE X
 $\beta = 0.259$

THE LOW STRESS VALUE INDICATES THAT A MUCH
HIGHER LOADING CAN BE TAKEN BY THE
MEMBER.

THE SAFE WORKING PRESSURE IS 85 PSI AS
LIMITED BY THE OUTER BOTTOM HEAL.

3. INCREASE IN LEAD VOLUME - CLOS. INF. HEAD
 COEFFICIENT OF EXPAN. - 1 IN. PAGE # 2 IS
 $28.8 \times 10^{-6} / \text{CU. IN.} / ^\circ \text{F}$

TEMPERATURES -

OPERATING - 150°F

AMBIENT - 70°F

$$\Delta T = 80^\circ \text{F}$$

LEAD VOLUME - CLOS. INF. HEAD = 11000 CU. IN.

INCREASE IN VOLUME -

$$V_2 = V_1 (\Delta T) C$$

$$V_2 = (11000)(80)(28.8 \times 10^{-6}) = 25.25 \text{ CU. IN.}$$

INCREASE IN LEAD VOLUME - CAS. P. 2, 4

TEMPERATURE -

OPERATING - 200°F

AMBIENT - 70°F

$$\Delta T = 130^\circ \text{F}$$

LEAD VOLUME - CAS. P. 2, 4 = 94010 CU. IN.

INCREASE IN LEAD VOLUME -

$$V_2 = V_1 (\Delta T) C$$

$$V_2 = (94010)(130)(28.8 \times 10^{-6}) = 352 \text{ CU. IN.}$$

4 - REQUIRED VOLUME OF EXPANSION VOID

CLOSURE HEAD -

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{(14.7)(25.35 + V_2)}{530} = \frac{(68)(V_2)}{610}$$

$$25.35 + V_2 = \frac{(530)(68)(V_2)}{(14.7)(610)}$$

$$25.35 + V_2 = 4.02 V_2$$

$$.249(25.35 + V_2) = V_2$$

$$6.32 + .249 V_2 = V_2$$

$$6.32 = V_2 - .249 V_2$$

$$6.32 = .751 V_2$$

$$V_2 = 8.4 \text{ IN}^3$$

$$\text{REQUIRED VOID} = V_1 = 25.35 + 8.4 = 33.75 \text{ IN}^3$$

CASK BODY -

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{(14.7)(352 + V_2)}{530} = \frac{(85)(V_2)}{660}$$

$$352 + V_2 = \frac{(530)(85)(V_2)}{(14.7)(660)}$$

$$352 + V_2 = 4.64 V_2$$

$$.215(352 + V_2) = V_2$$

$$75.8 + .215 V_2 = V_2$$

$$75.8 = V_2 - .215 V_2$$

$$V_2 = 96.6$$

$$\text{REQUIRED VOID} = V_1 = 352 + 96.6 = 448.6 \text{ IN}^3$$

$$P_1 = 14.7$$

$$P_2 = 68$$

$$T_1 = 70^\circ \approx 530^\circ \text{ R}$$

$$T_2 = 150^\circ \approx 610^\circ \text{ R}$$

$$V_1 = 25.35 + V_2$$

$$P_1 = 14.7$$

$$P_2 = 85$$

$$T_1 = 70^\circ \approx 530^\circ \text{ R}$$

$$T_2 = 200^\circ \approx 660^\circ \text{ R}$$

$$V_1 = 352 + V_2$$

5-DIMENSION AND LOCATION OF VOID CLOSURE HEAD

NO AFFECT ON SHIELDING
ADEQUACY

VOLUME OF VOID

$$\begin{aligned} 42^2 &= 1764 \\ 11^2 &= 121 \\ \hline 1643 &= \text{SAY } 40\frac{1}{2} \end{aligned}$$

$$\text{AREA} = \frac{(2.562)(.75)}{2} = .962 \text{ IN}^2$$

$$\begin{aligned} \text{VOLUME} &= (\pi)(23.708)(.962) = 71.6 \text{ IN}^3 \\ \text{REQUIRED VOLUME} &= 33.75 \text{ IN}^3 \end{aligned}$$

$$\begin{aligned} 13\frac{9}{16} &= 1\frac{1}{2} + \frac{3}{4} = 2\frac{1}{4} \\ 42 &= 42 - 2\frac{1}{4} = 39\frac{3}{4} \end{aligned}$$

$$\begin{aligned} 42^2 &= 1764.000 \\ 39\frac{3}{4}^2 &= 1560.062 \\ \hline 183.938 &= \text{SAY } 13\frac{9}{16} \end{aligned}$$

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5-DIMENSION AND LOCATION OF VOID CASK BODY

VOLUME OF VOID -

$$A = \left(\frac{4^2}{2}\right)(43.833)\pi = 1100 \text{ IN}^3$$

$$B = \left[(.1075) \left(\sqrt{3.75^2 + 3.75^2} \right) \right] (44)\pi = 418 \text{ IN}^3$$

$$V = A - B = 1100 - 418 = 682 \text{ IN}^3$$

$$\text{REQUIRED VOLUME} = 448.6 \text{ IN}^3$$

NO AFFECT ON SHIELDING ADEQUACY

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KNAPP MILLS INC.

WILMINGTON, DELAWARE

PIQUA-ELK RIVER REACTORS SPENT FUEL SHIPPING CASK

FINAL DESIGN REPORT

COO-1028-1

Issued April 1, 1963

Finalized May 29, 1964

TABLE OF CONTENTS

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II	Loading and Unloading Procedure
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V	Stress Analysis
VI	Fire Analysis
VII	Criticality Analysis
VIII	Miscellaneous Calculations

FINALIZED MAY 29, 1964

List of Changes and Additions - 5/29/64

- Section I - > Final Drawing List Added
 > Spare Parts List Added
 Cover Sheet Revised
- Section II - Entire Procedure Finalized
- Section VII - Basket Material Specification MS-3100-2 Added
 Cover Sheet Revised
- Section VIII - ERR 28 Assy Basket Thermal Analysis Added

REVISED 5/29/64

SECTION I

Introduction and Summary

INTRODUCTION

Intended Use of Cask
Reference Drawing List
Fuel Data and References
Final Drawing List
Spare Parts List

SUMMARY

Cask System Description
Structural Integrity
Resistance to Fire
Shielding Adequacy
Criticality Control
Decay Heat Removal
Test Program

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DRAWING LIST

<u>Drawing No.</u>	<u>Rev. No.</u>	<u>Title</u>
A-122	1	Weld Prep
A-124	0	Weld Prep
A-134	0	Sketch Plate
A-135	1	Adapter Casting
A-312	0	Baffle Plate
B-1018	2	Bellows Seal Globe Valve
C-1566	6	Fuel Assembly Adapter
C-1570	3	Space Envelope & Handling Socket Locations
C-1575	1	Thermocouple Assembly
C-1716	1	Adapter Handling Tool
C-1727	0	ERR 28 Assy. Basket Support Plate
F-2055, Sht. 1	9	Cask Body Fabrication Details
Sht. 2	5	Cask Body Machining Details
F-2056, Sht. 1	11	Closure Head Fabrication Details
Sht. 2	6	Closure Head Machining Details
Sht. 3	9	Closure Head Assembly
F-2058, Sht. 1	3	Shipping Structure Base
Sht. 2	3	Shipping Structure Strut Assembly
Sht. 3	5	Shipping Structure Assembly
F-2068	1	PNPF Fuel Basket Machining
F-2087	3	Miscellaneous Details
F-2096	3	General Assembly
F-2100	3	PNPF/ERR Fuel Basket Assembly
F-2102	5	Lifting Rig Details
F-2279	0	ERR 28 Assy Basket Final Machining
F-2280	1	ERR 28 Assy Basket Assembly

Material Specs

MS-3100-1	1	Fuel Assembly Basket - PNPF/ERR
MS-3100-2	0	Fuel Assembly Basket-ERR

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PIQUA ELK RIVER REACTORS
SPENT FUEL SHIPPING CASK

RECOMMENDED SPARE PARTS LIST

Item Description	Dwg.No.	Pc.No.	No.Per Cask	No. Spares		Remarks
				Stock	Order When Required	
Valve Disc (Teflon	B-1018	Disc	2	2	-	Drain & Vent Valves
Valve Stem Packing	B-1018	Packing	2	-	2	Drain & Vent Valves
Rubber "O" Ring	F-2056	9	2	2	-	Accessory Cavity
Rubber "O" Ring	F-2096	5	1	1	-	Cask Closure
Rubber "O" Ring	F-2096	6	1	1	-	Cask Closure
Aluminum Rupture Disc	F-2056	16	1	4	-	Specify BSB Lot#150296
Quick Disconnect (Female)	F-2056 F-2055	15 19	2	2	-	Drain & Vent Valves
Receptacle Cover & Gas- ket	C-1575	Cover & Gasket	4	1	-	Thermo- couple Receptacles
Studs & Nuts	F-2096	7,8	24Sets	6 Sets	-	Cask Closure
Hex Head Bolts	F-2096	7	24	6	-	Alternate to Studs & Nuts
Hex Head Bolts	F-2058	5	8	4	-	Shipping Structure
Hex Head Bolts & Nuts	F-2058	3,4	4Sets	2	-	Shipping Structure
Taper Bushing	F-2058	8	4	1	-	Shipping Structure
Wire Rope Assy's	F-2102	10	2	-	1	Lifting Yoke
Pressure Gage	F-2056	17	1	-	1	Accessory Cavity
Lead Seals	F-2096	15	3	Min . Order	-	
Lockwire	F-2096	9	As Req'd	100'	-	

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Loading and Unloading Procedures

I. Introduction

The Piqua-Elk River Reactor spent fuel shipping cask is designed for rail shipment between reactor and reprocessing sites. Using special equipment and with special highway permits, it is possible to ship the cask by truck also. The shipping weight of the cask loaded on the rail car is 32 tons. The loaded cask less shipping structures weighs 30 tons. Since there is no rail spur available at either plant, the cask is brought to the closest rail siding, transferred and transported to the reactor site on a low-boy truck.

The containment shell and equipment airlock design at both reactors requires that the cask be placed in horizontal position for entry through the airlock into the containment shell. Therefore the cask is designed to be handled in both horizontal and vertical positions. At the Piqua reactor, a special cask dolly and loading platform is provided to carry the cask through the airlock into the containment shell. At the Elk River reactor plant, a cask dolly is also used. However since the unloading level is considerably below the airlock level, an overhead monorail is provided to raise the cask and dolly to airlock level. The cask is then rolled through the airlock on rails in the same manner as at the Piqua Reactor Plant.

To facilitate the above described operations, a special lifting yoke is provided that is used to handle the cask in the vertical position and also for laying down in horizontal position. The cask is fitted with trunnion sockets at the lower end which engage pivoting trunnions on cask dolly. This trunnion-socket arrangement is provided for rotating the cask from vertical to horizontal position on the cask dolly. Since there are no crane facilities external to the containment shell at either plant, a 35-ton mobile crane is required. Inside the containment shell at both reactors, a 30-ton polar bridge crane is provided which is adequate for all cask handling operations.

The following general procedures are intended to cover the major operations and establish the proper sequence of these operations. Detailed step-by-step procedures for each reactor plant, factoring in local preferences as to specific equipment available and methods of accomplishing this type of work, must be prepared from these general procedures by reactor site personnel. These general procedures assume that the cask has been inspected for proper operating condition and shipped to the reactor site by rail ready to receive the fuel assemblies for the particular reactor. When

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5/20/64

Loading and Unloading Procedures (Continued)

I. Introduction (Continued)

Elk-River reactor fuel is to be shipped, it will be necessary to install the Elk River adapters in the dual purpose basket or install the 28 element ERR basket during inspection of the cask at the storage facility prior to shipment.

II. Loading Procedures

1. Remove tie-down bolts which attach shipping structure to rail car.
2. Using cask lifting yoke and mobile crane, lift cask and shipping structure as a unit from rail car and place on low-boy trailer.
3. Transport to area adjacent to containment shell airlock.
4. With no shims under shipping structure base corners and cask load resting in center of cask, remove pins at lower end of struts and remove bolts at upper end, tie back struts to allow cask to pass between struts.

PIQUA

ELK RIVER

5. Lift cask from shipping structure and place in vertical position on loading platform outside airlock.	Lift cask from shipping structure and place in vertical position below monorail in receiving area.
6. Washdown cask exterior.	Washdown cask exterior.
7. Using lifting yoke, lift cask, engage cask lower trunnion sockets with dolly trunnions and lower cask to horizontal position.	Using lifting yoke, lift cask, engage cask lower trunnion sockets with dolly trunnions and lower cask to horizontal position.
8. Open airlock doors and roll dolly into containment shell.	Roll dolly under monorail, hoist dolly and cask as a unit to building floor level.

Lower dolly onto dolly tracks, open airlock doors and roll dolly into containment shell. |
9. Using lifting yoke, lift cask from horizontal to vertical position and remove from dolly. Place in working area in vertical position.	
10. Perform final cleaning on cask exterior.	
11. Remove closure head nuts and accessory cavity cover.	

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II. Loading Procedures (Continued)

12. Attach closure head lifting lugs.
13. Engage lifting yoke with cask and attach closure head lifting cables to lifting lugs.
14. Lift cask and lower into loading pool.
15. Disengage lifting yoke from cask, remove closure head and place closure head and lifting yoke on pool floor or in other suitable area.
16. Load fuel assemblies.
17. Replace closure head and engage lifting yoke in upper cask trunnion sockets.
18. Raise cask to water level and replace four closure nuts.
19. Remove cask from pool, drain water from cask cavity, and decontaminate external surfaces. Smear test surface to measure activity.
20. Connect portable potentiometer to cask thermocouple receptacle terminals and commence recording inner shell temperature at regular intervals. Plot time-temperature curve to indicate approach to equilibrium. Cask must be vented through vent valve during approach to equilibrium.
21. During approach to equilibrium, sample air from cask at regular intervals for fission product activity. Select air flow to suit air monitoring equipment available. Plot activity-time curve to detect any increase in activity.
22. When temperature-time curve indicates temperature is "leveling off", replace and uniformly tighten remaining closure nuts in alternating sequence across diameter and rotating 90°.
23. Close vent valve and pressurize cask with air or inert gas to 5 psig. Using soap solution check closure seal, valves and rupture disc for leakage.
24. Survey cask external radiation levels on contact and at 3 meters. Record data.

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II. Loading Procedures (Continued)

25. Compile data from above tests and check compliance with 10 CFR 72.45 and 72.46. Use cask performance data from test results to predict fuel temperatures.
26. Close and lock vent and drain valves. Replace drain valve cover and accessory cavity cover.
27. Lower cask into horizontal position, place on dolly and remove from containment shell using previously described procedures.
28. With cask suspended from crane approximately 1/4" above shipping structure base, drop strut and upper ends against cask flange and install bolts in upper end of struts, Raise, lower, and rotate cask to align strut holes with cask. Make certain match marks agree.
29. With cask resting on center of base and no shims under corners of base, tighten bolts at upper end of struts and replace pins at lower end. Lockwire bolts and pins.
30. Transport to rail siding on low-boy and place cask and shipping structure on rail car. Place shims under four corners of base to place struts in compression.
31. Tie down shipping structure to rail car by bolting and/or welding. Ship lifting yoke and closure head lifting lugs in suitable box on rail car with cask.

III. Unloading Procedures

1. Inspect cask and shipping structure for any evidence of damage or malfunction upon receipt at reprocessing site. Wash road dirt from cask.
2. Remove pins from lower end of struts and bolts from upper ends.
3. Tie back struts to clear cask and, using lifting yoke, remove cask from rail car. Place cask in wash-down area.
4. Remove accessory cavity and drain valve cover plates.
5. Check cask temperature and pressure in preparation for cooldown.
6. Sample air activity in cask for fission products to detect possible fuel failure. Select air flow to suit monitoring equipment.

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III. Unloading Procedures (Continued)

7. Loosen closure nuts but leave hand tight.
8. Using cooldown procedure in COO-1028-2 as a guide, cooldown cask as required for immersion in unloading pool. Wash down cask external surface during cooldown.
9. Remove all but four closure nuts.
10. Install closure head lifting lugs, connect lifting yoke cables to lifting lugs, pick up cask and lower into unloading pool to water level
11. Remove remaining four closure nuts and lower cask to pool floor.
12. Disengage yoke and remove closure head. Place head and yoke on pool floor.
13. Unload fuel assemblies.
14. Replace closure head.
15. Remove cask from pool, drain water from internal cavity and place in wash down area.
16. Decontaminate cask.
17. Replace closure nuts and accessory cavity and drain valve cover plates. Remove closure head lifting lugs.
18. With cask suspended from crane approximately 1/4" above shipping structure base, drop struts against cask flange and install bolts at upper end of struts. Raise, lower and rotate cask to align bolt holes. Make certain match marks agree.
19. Replace and tighten pins at lower end of struts. Lockwire bolts at upper and lower end of struts.
20. Check rail car tie-down bolts to insure they are tight and return cask to shipper with lifting yoke and closure head lifting lugs.

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SECTION VII
Criticality Analysis

Analysis for Piqua Fuel
Reports on Elk River Fuel Reactivity
Report on A/C Analysis of Spiked Elements
Basket Material Specification MS-3100-1
Basket Material Specification MS-3100-2

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SECTION VIII
MISCELLANEOUS CALCULATIONS

Iodine Inventory in Cask
Fuel Pin Internal Pressure-ERR
Lead Expansion-Normal Conditions
Lead Expansion - Fire Conditions
Buoyant Force on Inner Shell during Fire
Basket - Inner Shell Differential Expansion during Fire
Radiation Streaming after Fire
ERR 28 Assy.Basket - Thermal Analysis

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5/29/64

KNAPP MILLS INC
WILMINGTON DELAWARE

PIQUA-ELK RIVER SPENT
FUEL SHIPPING CASK

PIQUA-ELK RIVER REACTORS

SPENT FUEL SHIPPING CASK

MATERIAL SPECIFICATION MS-3100-2

FUEL ASSEMBLY BASKET

Revision 0

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I. Scope

This specification covers the requirements for an aluminum alloy billet from which the Elk River Reactor spent fuel shipping cask fuel basket will be machined.

II. Material Specification

- a. The billet shall be forged of commercial 6061 aluminum ingot with a nominal one weight percent addition of Cadmium included in the basic alloy to obtain a uniform distribution of the Cadmium throughout the forged billet. The forged billet shall be delivered in the "O" (annealed) condition.
- b. The forged billet shall be free from voids, cracks, porosity or slag inclusions which would be visible to the naked eye after machining the external surfaces and boring the fuel cavities in the billet.
- c. The distribution of Cadmium in the billet shall be as uniform as possible and in no case shall any one ounce sample taken from any location in the billet contain less than 0.9 weight percent Cadmium.

III. Billet Dimensions

The forged billet as delivered shall be of such size to allow finish machining to 30 inches in diameter by 67-3/4 inches long allowing for surface irregularities and sufficient stock removal to get down to sound base metal. It is the billet suppliers responsibility to establish billet dimensions. However, in no case shall the dimensions of the billet if delivered rough machined be less than 30-1/2 inches in diameter by 67-3/4 inches long.

IV. Acceptance Tests

- a. Chemical and physical tests on the delivered billet normal to commercial work are required to assure compliance with the basic 6061-0 material specification. The aluminum content of the material may be one weight percent lower than the minimum specified for alloy 6061 to allow for the Cadmium addition. Notarized chemical and physical test reports shall be delivered with the billet.
- b. During machining Knapp Mills will collect approximately 140 samples of chips from various locations in the billet. The chips collected will be reduced to one ounce samples and analyzed by an independent laboratory for Cadmium content. All samples must comply with Section II-c of this specification.

REVISED 1/3/68

IV. Acceptance Tests (Continued)

- c. It is recommended, but not mandatory, that the billet supplier analyze samples taken from the billet external surfaces for Cadmium content and distribution prior to delivery of the billet.

REVISED 1/3/83

BASIC DATA

REACTOR POWER -WATTS	582 x 10 ⁶
OPERATING TIME-DAYS	640
LOAD FACTOR	100%
FUEL ASSEMBLY COOLING TIME-DAYS	120 MIN
RADIAL PEAKING FACTOR	1.45
AXIAL PEAKING FACTOR	1.12
FUEL ASSEMBLIES/CORE	148
ACTIVE LENGTH OF FUEL	60 INCHES
ACTIVE CORE DIAMETER	20 INCHES
REFERENCE DRAWINGS	CASK ASSY F-2096 FUEL BASKET F-2275

NOTES

ELK RIVER DATA FROM PHYSICS REPORT DATED 5-23-60,
USAREC FORM 434 DATED 7-8-60 AND FINAL HAZARDS
REPORT DATED JULY 8 1960.

DECAY HEAT CALCULATION

REFERENCE:- AERE-R-3216 APPENDIX F

A/CONE. IS/P/1071 - STEHN & CLANCY

THE STEHN & CLANCY DATA ARE USED IN PLACE OF
AERE R 3216 FIG 10 - BETA & TOTAL ENERGY
DECAY RATES, BECAUSE TOO LARGE AN EXTRAPOLA-
TION IS REQUIRED FOR $T_1 + T_0$.

COOLING TIME - $T_1 = 150$ DAYS

OPERATING TIME - $T_0 = 640$ DAYS

FROM STEHN & CLANCY DATA $P_1 + \lambda(\infty, T_1) = 5.06 \times 10^9$ MEV/S-W

$P_1 + \lambda(\infty, 150) = 5.06 \times 10^9$ MEV/SEC-WATT

$P_1 + \lambda(\infty, 150 + 640) = 2.66 \times 10^9$ " " "

$\Delta P_1 = \frac{5.06 \times 10^9 - 2.66 \times 10^9}{2.66 \times 10^9}$ " " "

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THE HEAT LOAD PER FOOT PER AVERAGE ASSEMBLY IS

$$Q = 2.40 \times 10^9 \times 58.2 \times 10^6 \times 1.6 \times 10^{-13} \times 3.413 / 148$$

$$= 515 \text{ BTU/HR}$$

THE LOCAL HOTSPOT CONDITION IS

$$Q_{HS} = 515 \times 1.45 \times 1.72 \times 12 / 60$$

$$= 257 \text{ BTU/HR/FT}$$

THE HEAT LOAD ON THE CASE EXTERNAL SURFACE WILL BE BASED ON (28) TWENTY EIGHT FUEL ASSEMBLIES FROM THE CENTER REGION OF THE ELK RIVER CORE.

$$Q = 28 \times 515 \times 1.45 = 20,900 \text{ BTU/HR}$$

THE EXTERNAL SURFACE IS FINNED OVER A HEIGHT OF $6\frac{1}{2}$ FEET MINIMUM. THE INTERNAL BASKET WILL BE 66 INCHES LONG MINIMUM. THE EFFECTIVE HEIGHT FOR HEAT DISSIPATION LIES IN THESE LIMITS. AXIAL CONDUCTION IN THE HIGH CONDUCTIVITY ALUMINUM BASKET WILL NORMALIZE THE AXIAL PEAKING FACTOR AND AXIAL CONDUCTION IN THE LEAD WALL WILL FURTHER SPREAD THE HEAT ALONG THE 66" BASKET HEIGHT. ASSUME THAT 76" OF FIN LENGTH IS EFFECTIVE FOR DISSIPATION. THE HEAT LOAD PER FOOT DUE TO THE FUEL IS THEN

$$Q_e = 20900 / 6.33 = 3300 \text{ BTU/HR/FT}$$

THE CONTRIBUTION DUE TO SOLAR HEATING CAN BE DETERMINED AT THIS POINT. REF MARKS HDBK 6TH. ED. P. 12-114 THE MAXIMUM SOLAR HEAT FLUX OF PRACTICAL INTEREST WILL OCCUR ON A SEPTEMBER AFTERNOON WHEN IT IS POSSIBLE TO HAVE A COMBINATION OF 100°F AMBIENT & A HIGH SOLAR HEAT FLUX. THE SOLAR HEAT FLUX IS

$$Q_s = CFTA(\cos \alpha) \quad \text{IN BTU/FT}^2\text{-HR}$$

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WHERE:-

$C \equiv$ MEAN SOLAR CONSTANT - 442 BTU/FT²-HR.
 $F \equiv$ ANNUAL VARIATION 0.965 IN JUNE, 1.0365 IN DEC.
 $T \equiv$ ATMOSPHERIC TRANSMITTANCE - 0.6
 $A \equiv$ ABSORPTIVITY OF SURFACE - 0.4
 $\chi \equiv$ ANGLE OF INCIDENCE TO HORIZONTAL SURFACE
 $\cos \chi = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega$ WHERE
 $\phi \equiv$ LATITUDE - 45° N
 $\delta \equiv$ DECLINATION OF SUN 0° - SEPT. 21
 $\omega \equiv$ HOUR ANGLE 60° (W) 4 PM - AFTERNOON

$$\cos \chi = 0.707(0) + 0.707(1)0.5 = 0.353$$

$$\chi = 72.4^\circ \text{ ON HORIZONTAL SURFACE}$$

$$\text{ON VERTICAL CASE SURFACE } \chi = 17.6^\circ$$

SUBSTITUTING WE HAVE

$$Q_s = 442(1)(0.6)(0.4)(0.35) = 101 \text{ BTU/FT}^2\text{-HR}$$

CONVERTING TO BTU/LIN/FT WE HAVE

$$Q_s = 36\pi \times 1 [101] = 1250 \text{ BTU/HR/FT}$$

$$Q = Q + Q_s = 3550 + 1250 = 4800 \text{ BTU/HR/FT}$$

ELK RIVER CASE
CROSS-SECTION

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TEMPERATURE DISTRIBUTION CALCULATION

$$Q = h_c A_c (T_i - T_a) + \epsilon \sigma A_r (T_i^4 - T_a^4) \quad \text{BTU/HR-FT}$$

$h_c \equiv$ TRANSFER COEFFICIENT BTU/HR-FT²-°F-FT

$A_c \equiv$ AREA EFFECTIVE FOR CONVECTION

$A_r \equiv$ AREA EFFECTIVE FOR RADIATION

$\epsilon \equiv$ EMISSIVITY = 0.9 (PAINTED STEEL SURFACE)

$\sigma \equiv$ STEFAN-BOLTZMAN CONSTANT

$T_a \equiv$ AMBIENT TEMPERATURE = 100°F

THE EXPOSED CASK SHELL AND EFFECTIVE FIN AREA IS

$$\text{NO OF PINS} = 48\pi/2 = 75.4 \quad \text{USE 72 PINS}$$

$$\text{SHELL AREA} = [48\pi - 72(0.25)]/12 = 11.1 \text{ FT}^2$$

$$\text{FIN AREA} = 6.25(72)/12 = 37.5 \text{ FT}^2$$

$$\text{FIN EFFICIENCY} = \eta_f = \tanh N/N$$

$$N = w\sqrt{(h_c/k_f Y)} \quad \text{WHERE}$$

$w =$ FIN WIDTH - FT

$h_c =$ TRANSFER COEFFICIENT ≈ 0.70

$k_f =$ FIN CONDUCTIVITY

$Y =$ FIN HALF THICKNESS

$$N = 0.25\sqrt{(0.1/26 \times 0.0104)} = 0.403$$

$$\eta_f = \tanh(0.403)/0.403 = 0.95$$

$$A_c = 11.1 + 0.95(37.5) = 46.7 \text{ FT}^2$$

$$A_r = 54\pi/12 = 14.1 \text{ FT}^2$$

$$h_c = 0.19 (T_i - T_a)^{1/3}$$

ASSUME T_i IS 180°F

$$h_c = 0.19(80)^{1/3} = 0.816$$

$$Q = 0.816(46.7)80 + 0.9(14.1)(0.174)(1680 - 982)$$

$$= 3050 + 1540 = 4590 \text{ BTU/HR-FT}$$

THEREFORE ($T_i = 180^\circ\text{F}$) AND THIS IS THE CASK SHELL TEMPERATURE AT THE BASE OF THE PINS.

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CALCULATE T_2 —

$$T_2 = (Q \text{ LNC. } R_1 / 2\pi L K) + T_1$$

ASSUME LEAD METALLURGICALLY BOUNDED TO NUBER AND
CIPER SHELLS, NEGLECT STEEL SHELL THICKNESSES
AND ASSUME WALL OF 3/4 IN. SOLID LEAD. FOR THIS
CALCULATION THE MAXIMUM HEAT RELEASE PER
FOOT OF SHELL ASSEMBLY IS USED AND NO CREDIT
IS TAKEN FOR AXIAL CONDUCTION.

$$Q = Q_{\text{max}} = 237 \text{ BTU/HR/FT FOR 450°}$$

$$R_1 = 24 \text{ IN.}$$

$$R_2 = 14 \text{ IN.}$$

$$K = 12$$

$$L = 1 \text{ FT}$$

$$T_2 = \frac{237 \times 24 \times 24 \times 450}{2 \times \pi \times 14 \times 12} + 180$$

$$= 200 + 180 = 210^\circ$$

CALCULATE MAXIMUM TEMPERATURE T_3 IN T_2 —

THE BARRIER WILL BE DESIGNED SO THAT UNDER
LESSER COOLANT CONDITIONS THE DIFFERENTIAL
EXPANSION BETWEEN THE BARRIER AND JACK
WILL CLOSE THE CLEARANCE GAP BETWEEN THESE TWO
PARTS AND MINIMIZE THERMAL RESISTANCE AT THIS
INTERFACE, EVEN THOUGH THE BARRIER WILL BE DE
SIGNER TO EXPOSE AN UNCOATED THE SHELL, ASSUME
THAT ACTUAL CONTACT AT CONTACT DOES NOT DEVELOP
BECAUSE OF SURFACE IRREGULARITIES. IT IS SAFE
TO ASSUME AN AVERAGE AIR GAP OF 0.010" EXISTS
AT THE INTERFACE FOR THE PURPOSE OF CALCULA
TION. FROM EXPERIENCE HAS BEEN OBSERVED
WITH SYSTEMS OF THIS TYPE THAT ACTUAL LOCAL
CLEARANCE VALUES VARY FROM 0 TO 0.008". THUS
THE CALCULATION WILL BE CONSERVATIVE.
NEGLECTING RADIATION OF THE SURFACE IS

$$T_3 = Q \times CA + T_2$$

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$$\begin{aligned} & \dots = \dots \\ X & = \dots / 2 = \dots \\ Y & = \dots \\ A & = \dots \end{aligned}$$

$$\begin{aligned} T_3 & = \dots \\ & = \dots \end{aligned}$$

BASKET TEMPERATURE DISTRIBUTION

THE ACTUAL AIR FLOW THROUGH THE ASSEMBLY IS
IN THE BASKET IS GIVEN ON PAGE 3 AND ON PAGES
F-2280 AND F-2219. THE PURPOSE OF THIS
ANALYSIS IS TO PROVIDE A TEMPERATURE DISTRIBUTION
BOTH IN THE Y DIRECTION AND
3/4 IN THE X DIRECTION. THE BASKET UNIT DOES
NOT LEAD ITSELF TO SIMPLE ANALYSIS; HOWEVER
THE PROBLEM CAN BE CONSIDERED AND APPROXIMATED
BY A MODEL AS SHOWN ON PAGE 1 WHICH HAS
8 ASSEMBLIES IN A 2-DIMENSIONAL SYMMETRICALLY.
IT IS ASSUMED THAT THE AIR FLOW IS THE SAME
AS SHOWN IN A WILL AT THE TIME WHEN THE AIR FLOW
AND IN TURN THE AIR FLOW IN THE BASKET WILL
BE AT THE HIGHEST FUEL TEMPERATURE. THEREFORE
IT IS SUFFICIENT TO CALCULATE ONLY FUEL TEMPERATURE
IN THE BASKET. IT CAN BE CONSERVATIVELY
ASSUMED THAT ALL HEAT FROM ASSEMBLIES A, B & C
FLOWS EQUALLY BETWEEN BOUNDARY PLANES X-X' OR
Y-Y'. THIS ASSUMPTION WILL YIELD THE
BASKET TEMPERATURE AND THE ASSEMBLY A. USING
THIS TEMPERATURE, MAXIMUM FUEL TEMPERATURE IN
ASSEMBLY A WILL BE CALCULATED.

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ANALYTICAL MODEL OF RACKET

ASSUME ALL HEAT FROM A & C FLOWS THRU SECTION "D"

$$\Delta T = QX / KA$$

$$Q = 3 \times 257, X = 1.31/12$$

$$K = 85, A = 4.5 \times 1/12$$

$$\Delta T = \frac{3 \times 257 \times 1.375}{85 \times 4.5}$$

$$= 2.77 \text{ SAY } 3^\circ \text{F}$$

ASSUME ALL HEAT FROM A & B FLOWS THRU WALLS AT SECTION "C", WHILE HEAT FROM ELEMENT "C" IS ADDED UNIFORMLY ALONG WALLS OF SECTION "C".

$$\Delta T_{AB} = \frac{2 \times 257 \times 3.625}{85 \times .875} = 25.1^\circ$$

$$\Delta T_C = \frac{1 \times 257 \times 3.625}{2 \times 85 \times .875} = 6.27^\circ$$

$$\Delta T = 25.1 + 6.27 = 31.37 \text{ SAY } 32^\circ \text{F}$$

ASSUME ALL HEAT FROM A & B FLOWS THRU B6-5

$$\Delta T = \frac{2 \times 257 \times 1.125}{85 \times .875} = 7.77^\circ \text{ SAY } 8^\circ \text{F}$$

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ASSUME ALL HEAT FROM "A" FLOWS THRU WALLS AT SECTION "B", & HEAT FROM ELEMENT "B" IS ADDED UNIFORMLY ALONG WALLS OF SECTION "B".

$$\Delta T_A = \frac{1 \times 257 \times 3.625}{85 \times .875} = 12.5^\circ$$

$$\Delta T_B = \frac{1 \times 257 \times 3.625}{2 \times 85 \times .875} = 6.3^\circ$$

$$\Delta T = 12.5^\circ + 6.3^\circ = 18.8^\circ \text{ SAY } 19^\circ \text{F}$$

ASSUME ALL HEAT FROM A FLOWS THRU AB-7

$$\Delta T = \frac{1 \times 257 \times 1.125}{85 \times .875} = 3.9^\circ \text{ SAY } 4^\circ \text{F}$$

ASSUME ALL HEAT FROM A IS ADDED UNIFORMLY ALONG WALLS OF SECTION "A"

$$\Delta T = \frac{1 \times 257 \times 1.125}{85 \times .875} = 3.9^\circ \text{ SAY } 4^\circ \text{F}$$

THE SUM OF THESE TWO TEMPERATURE DIFFERENCES IS 7.3°. ADDING TO EXISTING OD TEMPERATURE OF 251° THE RESULT AN UPPER LIMIT BURNER TEMPERATURE AROUND 258° ASSUMED AS OF 254°F. USING THIS TEMPERATURE AS THE UNIFORM HEAT SINK TEMPERATURE COMPLETELY SURROUNDING THE ASSUMED "A" WILL YIELD AN UPPER LIMIT FUEL TEMPERATURE. FURTHERMORE, HEAT TRANSFER FROM FUEL TUBES TO EXHAUST AND FROM EXHAUST-FIN WITHIN FUEL ASSEMBLY WILL BE BASED ON RADIATION AND CONDUCTION ONLY; CONVECTION WILL BE ASSUMED NEGLIGIBLE. THE BASIC EQUATION FOR HEAT TRANSFER THEN IS:

$$Q = \frac{K}{x} A_c \Delta T + F \epsilon' \sigma A_r (T_2^4 - T_1^4) \text{ WHERE:}$$

A_c = AREA EFFECTIVE FOR CONDUCTION

A_r = AREA EFFECTIVE FOR RADIATION

F = GEOMETRIC VIEW FACTOR FOR RADIATION

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ANALYTICAL MODEL

450" DIA ---
3/4" PITCH
T1, T2

3/4" SQ ---
MAX CRACK SIZE
AT 324°F

FIRST ROW PIN TEMPERATURE = T1

ASSUME 1/2 PIN CIRCUMFERENCE IS EXPOSED FOR CONVECTION AREA IN AN AREA INCHES ALL GAP

$$A_c = \left[12 \left(\frac{450}{12} \right) \frac{\pi}{2} + 4 \left(\frac{450}{12} \right) \frac{3\pi}{4} \right] = 1.04 \text{ FT}^2 / \text{FT LENGTH}$$

$$\bar{X} = \frac{0.125 - 0.25 \sin 90^\circ}{12} = 0.018 \text{ FT}$$

ADDITIONAL PERIMETER FOR THERMAL CONVECTION FOR RELIABILITY

$$A_R = \left[\left(\frac{1 \times 3}{12} \right) + 4 \left(\frac{450}{12} \right) \frac{\pi}{4} \right] = 1.12 \text{ FT}^2 / \text{FT LENGTH}$$

WITH A_R CALCULATED THE SURF. HEATING COEFF. IS 1.0.

$$E' = \frac{1}{\frac{1}{E_p} + \frac{1}{E_B} - 1}$$

$E_p = 0.7$ COARSE SST PINS AFTER OPEN AT 324°F IN REACTION

$E_B = 0.1$ CLEVER BRIDGE ALUMINUM KINSLET

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$$E' = \frac{1}{\frac{1}{0.1} + \frac{1}{0.1}} = 0.05$$

$$T_{12} = T_{11} = 440' \quad K = F = 12$$

$$Q = \frac{0.05}{0.08} (1.04) (111,000 - 1190) = 141 + 5 = 146$$

$$T_{12} = T_{11} = 440'$$

$$Q = \frac{0.05}{0.08} (1.04) (112,000 - 1190) = 140 + 5 = 145$$

$$T_{12} = T_{11} = 440'$$

$$S_{12} = K = 12$$

REMARK: ... AT TRUSS F ...
THE TARE ...
KNOW AT ...

$$S_{12} = 257 \cdot \frac{1}{12} = 21.4$$

$$\frac{1.1}{1.1} = 1$$

$$\bar{X}_1 = \frac{257 - 257 \cdot 1.1}{12} = 0$$

$$A_c = \left[4 \left(\frac{4.1}{12}, \frac{\pi}{4} \right) + 4 \left(\frac{4.50}{12}, \frac{\pi}{4} \right) \right] = 0.512$$

$$A_{12} = \left[4 \left(\frac{1.5}{12}, \frac{\pi}{4} \right) + 4 \left(\frac{1.50}{12}, \frac{\pi}{4} \right) \right] = 0.375 \text{ FT}^2$$

$$E' = \frac{1}{\frac{1}{0.1} + \frac{1}{0.1}} = 0.05$$

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TRY $T_{12} = 520^{\circ}\text{F}$ $K @ 500^{\circ}\text{F} = .0246$

$$Q = \frac{.0246}{.036} (0.570)(50) + (.538)(.618)(1570 - 1290)$$

$$= 20 + 100 = 120 \text{ TOO HIGH}$$

TRY $T_{12} = 510^{\circ}\text{F}$ $K @ 490^{\circ}\text{F} = .024$

$$Q = \frac{.024}{.036} (0.590)(40) + (.538)(.618)(1530 - 1290)$$

$$= 15 + 19 = 34 \text{ OK } > 40$$

NEUTRON COLD PIN TEMP = $\underline{510^{\circ}\text{F}} - T_{12}$

CENTER PIN TEMP T_3

$$Q = \frac{1}{25} \times 251 = 10.0 \text{ BTU/HR}$$

$$A_c = A_k = \frac{450 \pi}{12} = .118 \text{ F}^{-2} / \text{FT LENGTH}$$

NEGLECT CONDUCTION ENTIRELY

$$Q = (.538)(.118)(T_3^4 - 1530)$$

TRY $T_{13} = 535^{\circ}\text{F}$ $Q = 10.5$

CENTER PIN TEMP = $\underline{535^{\circ}\text{F}}$ MAX FUEL TEMP.

THIS UPPER LIMIT FUEL TEMPERATURE IS WELL BELOW REACTOR OPERATING TEMPERATURE OF 618°F (CLADDING MAX). THEREFORE, DRY SHIPMENT OF 28 EKK FUEL ASSEMBLIES 150 DAYS AFTER SHUTDOWN IS POSSIBLE. USING TEST RESULTS ON ACTUAL CASK IN COO-1028-2" TEST REPORT" SHIPPING TIME COULD BE IMPROVED CONSIDERABLY IF DESIRED.

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PIQUA-ELK RIVER REACTORS
SPENT FUEL SHIPPING CASK

FINAL DESIGN REPORT

TABLE OF CONTENTS

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II	Loading and Unloading Procedure
III	Shielding Analysis
IV	Thermal Analysis
V	Stress Analysis
VI	Fire Analysis
VII	Criticality Analysis
VIII	Miscellaneous Calculations

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Loading and Unloading Procedures (Continued)

I. Introduction (Continued)

Elk-River reactor fuel is to be shipped, it will be necessary to install the Elk River adapters in the basket during inspection of the cask at the storage facility prior to shipment.

II. Loading Procedures

1. Remove tie-down bolts which attach shipping structure to rail car.
2. Using cask lifting yoke and mobile crane, lift cask and shipping structure as a unit from rail car and place on low-boy trailer.
3. Transport to area adjacent to containment shell airlock.
4. Remove "A" frames from cask and shipping structure.

PIQUA

ELK RIVER

5. Lift cask from shipping structure and place in vertical position on loading platform outside airlock.	Lift cask from shipping structure and place in vertical position below monorail in receiving area.
6. Washdown cask exterior.	Washdown cask exterior.
7. Using lifting yoke, lift cask, engage cask lower trunnion sockets with dolly trunnions and lower cask to horizontal position.	Using lifting yoke, lift cask, engage cask lower trunnion sockets with dolly trunnions and lower cask to horizontal position.
8. Open airlock doors and roll dolly into containment shell.	Roll dolly under monorail, hoist dolly and cask as a unit to building floor level.

Lower dolly onto dolly tracks, open airlock doors and roll dolly into containment shell. |
9. Using lifting yoke, lift cask from horizontal to vertical position and remove from dolly. Place in working area in vertical position.	
10. Perform final cleaning on cask exterior.	
11. Remove closure head nuts and accessory cavity cover.	

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II. Loading Procedures (Continued)

12. Attach closure head lifting lugs.
13. Engage lifting yoke with cask and attach closure head lifting cables to lifting lugs.
14. Lift cask and lower into loading pool.
15. Disengage lifting yoke from cask, remove closure head and place closure head and lifting yoke on pool floor or in other suitable area.
16. Load fuel assemblies.
17. Replace closure head and engage lifting yoke in upper cask trunnion sockets.
18. Raise cask to water level and replace four closure nuts.
19. Remove cask from pool, drain water from cask cavity, and decontaminate external surfaces. Smear test surface to measure activity.
20. Connect portable potentiometer to cask thermocouple receptacle terminals and commence recording inner shell temperature at regular intervals. Plot time-temperature curve to indicate approach to equilibrium. Cask must be vented through vent valve during approach to equilibrium.
21. During approach to equilibrium, sample air from cask at regular intervals for fission product activity. Select air flow to suit air monitoring equipment available. Plot activity-time curve to detect any increase in activity.
22. Replace and tighten remaining closure nuts in accordance with sequence in Figure 1 (to be developed).
23. Close vent valve and pressurize cask with air or inert gas to 5 psig. Using soap solution check closure seal, valves and rupture disc for leakage.
24. Survey cask external radiation levels on contact and at 3 meters. Record data.

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II. Loading Procedures (Continued)

25. Compile data from above tests and check compliance with 10 CFR 72.45 and 72.46. Use cask performance data from test results to predict fuel temperatures.
26. Lower cask into horizontal position, place on dolly and remove from containment shell using previously described procedures.
27. Place cask in its shipping structure and install "A-Frame" braces.
28. Transport to rail siding on low-boy and place cask and shipping structure on rail car.
29. Tie down shipping structure to rail car.
30. Close and lock vent and drain valves. Replace drain valve cover and accessory cavity cover.

III. Unloading Procedures

1. Inspect cask and shipping structure for any evidence of damage or malfunction upon receipt at reprocessing site. Wash road dirt from cask.
2. Remove shipping structure "A" frame braces and, using lifting yoke, remove cask from rail car. Place cask in wash-down area.
3. Remove accessory cavity and drain valve cover plates.
4. Check cask temperature and pressure in preparation for cooldown.
5. Sample air activity in cask for fission products to detect possible fuel failure. Select air flow to suit monitoring equipment.
6. With cask vented through vent valve, connect steam supply (15 psi max.) to drain valve and commence steam cooldown.

Note: Detailed cooldown procedures will be developed from test data to be obtained during thermal test program.

7. During cooldown, wash down cask exterior.
8. When cask inner shell temperature as indicated by cask thermocouples and steam temperature at vent valve are below 200°F and 250°F respectively, disconnect steam supply and connect water supply to drain valve.

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III. Unloading Procedures (Continued)

9. Complete cooldown operation by admitting water to cask at a maximum rate of 5 GPM. Fill cask and circulate water through cask until water temperature at vent valve is less than 100°F.
10. Loosen all closure nuts and remove all but four of the nuts.
11. Install closure head lifting lugs, connect cables to lifting yoke, pick up cask and lower into unloading pool to water level.
12. Remove remaining four closure nuts and lower cask to pool floor.
13. Disengage yoke and remove closure head. Place head and yoke on pool floor.
14. Unload fuel assemblies.
15. Replace closure head.
16. Remove cask from pool, drain water from internal cavity and place in wash down area.
17. Decontaminate cask.
18. Replace closure nuts and accessory cavity and drain valve cover plates. Remove closure head lifting lugs.
19. Place cask in shipping structure and replace "A" frame braces.
20. Check rail car tie-down bolts to insure they are tight and return cask to shipper.

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C. RESISTANCE TO FIRE

The cask has been analyzed to determine its ability to withstand the standard one-hour fire test. Since the time temperature curve specified for the fire test is based on thermocouple temperatures in a furnace atmosphere, it has been necessary to first calculate the flame temperature or furnace atmosphere which would produce the thermocouple response specified for the standard one-hour fire. This has been done in the analysis and a time temperature curve of the furnace atmosphere has been developed. This curve is the basis for computing the heat flux to which the cask is subjected.

The effect of this fire atmosphere on the cask has been calculated using two basically different approaches. First, the cask is treated as a mass of lead and steel of infinite thermal conductivity. This approach yields upper limit internal temperatures because no credit is taken for the insulating effect of the lead shielding. The result of this calculation is used in further analysis of fuel temperatures at the end of the fire. The second approach considers a unit area of cask outer shell subjected to the fire atmosphere and, by using an iterative process considering the variation in fire temperature and cask temperature, the temperature gradient through the cask wall is calculated. This analysis yields the maximum outer shell temperature to be expected and the results of this approach are used to further evaluate structural integrity of the shield envelope.

The results of the first analysis yields a bulk temperature of 785°F. This means that the upper limit temperature of the fuel basket at the end of the one-hour fire would be 785°F. The temperature increase due to decay heat release is negligible because the heat capacity of the fuel and basket is such that the temperature increase due to this heat source is less than 50°F during the one-hour fire. Using the temperature differences calculated in the thermal analysis, pages 9 through 26, the upper limit fuel temperatures at the end of the one-hour fire can be calculated. In the case of Piqua fuel, the temperature difference between fuel and basket previously calculated was 231°F, that for the Elk River fuel was 313°F. Adding these temperature differences to the 785°F basket temperatures gives an upper limit fuel temperature of 1016°F for Piqua fuel and 1098°F for Elk River fuel. This is a conservative extrapolation because the temperature differences previously calculated would be less due to increase in the radiation mode of heat transfer at higher temperatures.

In the case of the Piqua fuel, cladding failure is not likely to occur because the melting point of the clad is 1200°F and the upper limit cladding temperature estimated is 1016°F. In the case of Elk River fuel, the internal pressure in the fuel pins due to fission gas and helium at 1098°F is approximately 425 psi. The induced stress in the fuel pin cladding under these conditions is 4400 psi. These values are based on 10,000 MWD/T burnup and 10 % fission gas release. (See data in Misc. Calculations Section). The tensile strength of the 304 SS cladding at 1100°F is greater than 50,000 psi. Therefore, an

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adequate margin of safety on cladding failure exists at the end of the one-hour fire. As an added consideration, it is noted that even if cladding failure should occur, the total I-131 content of the cask that could be released is far less than 10 curies (See Misc. Calculation Section).

The results of the calculation of the temperature gradient through the cask wall indicate a maximum outer shell temperature of 1260°F and an innershell temperature of 660°F. This means that complete melting of the lead will occur, and that the differential expansion between the steel and lead must be accommodated. The differential expansion is provided for by plastic deformation of the shield envelope. This is a completely sound concept and eliminates the undesirable effects of providing large expansion spaces within the shield envelope. The plastic deformation required to accommodate the differential expansion is less than 2% which is far less than would be required for failure of the shield envelope material. The internal pressure in the shield envelope is also minimized because of the fact that the internal pressure is solely governed by the yield strength of the outer shell which is considerably reduced at the calculated outer shell temperature. There is no danger of this pressure collapsing the innershell because it is well supported by the fuel basket. Deflection of the flat plates in the closure head and the bottom of the cask cavity is also of no concern because in both areas the worst case conditions are still far from the failure point. Therefore it is concluded that the cask is capable of withstanding the one-hour fire without rupture of the shield envelope or uncontrolled release of radioactivity.

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D. SHIELDING ADEQUACY

The cask and closure head shielding has been designed to meet requirements of 10 Mr/Hr. at three meters from and 200 Mr/Hr on contact with any accessible surface. For the radial shield, 10 Mr/Hr at three meters is limiting; for the closure head and cask bottom, 200 Mr/Hr on contact is limiting. Shielding calculations are based on infinite operation at full power and 120 days decay time prior to loading. The results of the calculations indicate that 8-3/4" equivalent lead is required in the radial shield, 7-1/2" equivalent lead in the closure head and 8" equivalent lead in the cask bottom. In the final closure head drawings an extra 1/2" of lead has been included to reduce radiation levels approximately a factor of two on the closure head. This is to reduce radiation exposure of personnel during cask unloading at the reprocessing site.

The lead shielding is metallurgically bonded to the inner and outer shells of the cask body and the closure head. This improves structural integrity of the cask and insures that the shielding will remain in its intended position over the life of the cask. All penetrations are curved or stepped to eliminate the possibility of radiation streaming through the shield. A small void space is provided at the bottom corner of the cask to provide for the small amount of differential expansion between the steel and lead shielding in going from ambient to operating temperatures.

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E. CRITICALITY CONTROL

A preliminary analysis of the cask loaded with 19 Piqua or 19 Elk-River fuel assemblies indicated that the load of Piqua elements is limiting with respect to criticality. Further analysis of the Piqua condition showed that the need for a neutron poison was marginal. Therefore the decision was made to include a neutron poison in the aluminum fuel basket. The poison selected is Cadmium which is alloyed with the 6061 aluminum billet from which the basket will be machined. Addition of the neutron poison to the basket provides more than adequate safety margin for the loading of Piqua and Elk-River fuel assemblies and also provides for future use of the cask with higher fuel enrichments. The basket material specification calls for one weight percent nominal Cadmium addition with 0.5 weight percent minimum in any sample. Approximately 100 samples will be taken from various areas during machining of the basket and these samples will be analyzed for Cadmium to determine compliance with specification.

Since the Piqua case is limiting, a detailed analysis of this condition with 0.5 w/o Cadmium added to the basket was performed. Two methods of analysis were used and both methods were checked for validity against criticality data furnished by Atomics International. Both methods agreed within $0.04\Delta K$. However, to be safe, the method predicting the highest K_{eff} was used as the design value. An analysis of the cask without Cadmium present was also performed for additional information. The results of the calculations are as follows:

<u>Condition</u>	<u>k_{eff}</u>	<u>k_{∞}</u>
Cask Unpoisoned	0.824	1.066
Cask Poisoned-0.5 w/o CD	0.722	.934

No detailed analysis of the cask loaded with 19 normal Elk-River elements was required since start-up data from the plant has shown that the minimum number of elements required for criticality is 30. Therefore the requirement that the cask load not exceed 75% of the minimum number of elements required for criticality is met and no further analysis is required. This applies only to the 4.3% enriched normal Elk-River elements. Even though there is no intention of loading the cask with 5.2% enriched spiked elements, Allis-Chalmers in an independent analysis has considered this condition. They have reported that as few as 20 spiked elements can be critical and, therefore, the cask loaded with 19 spiked elements would be marginal with respect to safety. In the Allis-Chalmers analysis no credit is taken for Cadmium in the aluminum basket. However, they do consider the poisoning effect of the aluminum alloy itself. The results of their calculation yield a k_{eff} of 0.88 with no specification as to the uncertainty factor to be applied to this value. However, based on the Piqua analysis, it is expected that this value would decrease approximately $0.10\Delta K$ by considering the Cadmium present, and therefore the cask is safe with respect to criticality even if loaded with the 5.2% enriched Elk-River elements.

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F. DECAY HEAT REMOVAL

An important objective of the cask design has been to develop a decay heat removal system adequate to limit fuel temperatures under normal conditions and without liquid coolants to acceptable levels. This has been accomplished by placing the fuel assemblies in close fitting cavities in a cylindrical aluminum basket. A controlled clearance gap, adequate for removal and replacement of the basket, is provided between basket and cask cavity. After fuel is loaded and the system temperatures reach equilibrium, the differential expansion between the basket and innershell closes the gap thus providing efficient conduction of heat from basket to innershell. The heat is then transferred by conduction through the cask wall to the outer shell where it is dissipated by natural convection to the surrounding air. The lead shielding is metalurgically bonded to inner and outer shells to eliminate thermal resistance at these interfaces.

The cask design has been analyzed with a full load of both Piqua and Elk-River fuel to determine fuel temperatures in an air-filled, unpressured cask. In both cases it has been assumed that the fuel has operated at full power for its design life (640 days-Elk River, 515 days-Piqua) and allowed to decay 120 days prior to loading. The maximum temperatures calculated are as follows:

	<u>Piqua</u>	<u>Elk River</u>
Fuel -°F	590	618
Outer Shell -°F	181	166

The fuel temperatures do not exceed corresponding reactor operating temperatures. Therefore, the cask can be shipped normally dry.

Considering the effect of solar heating on one side of the cask, the local maximum outer shell temperature in the finned area is 197°F. The temperature drop in the fin is approximately 10°F which gives a accessible surface temperature of 187°F. This temperature would require that a guard rail or screen be placed around the cask during transport to protect personnel. However, since it is expected that test results will show sufficiently improved thermal performance to eliminate this problem, the decision on the protective guard rail or screen requirement will be deferred until test results are available.

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G. TEST PROGRAM

A test program will be carried out on the cask system to demonstrate adequacy in all areas. This test program will cover the following major areas:

1. Shielding Inspection
2. Mechanical Fit of Mating Parts
3. Hydrostatic Test for Structural Integrity
4. Leak Test for Leak Tightness
5. Thermal Test
6. Handling Test

These tests will be carried out during manufacture and final assembly at the appropriate times. Detailed procedures will be prepared for the Shielding Inspection and Thermal Tests. Other tests will be covered by normal Quality Control check-off lists.

The scope of the tests outlined above is as follows:

Shielding Inspection

The cask body and closure head will be inspected for shield soundness by the Knapp patented gamma probing process. This process utilizes a high-strength, high energy radioactive source, a scintillation type detector, spectrometer analyzer and strip-chart recorder. Nominally 100% of the closure head and cask wall shielding will be inspected excluding local projections, penetrations, shield discontinuities, etc. Inspection of the cask bottom shielding by the gamma probe process is not required. Shield soundness in this area is assured by witnessing pouring and shrink-cooling operation. This is possible because the cask is poured in an inverted position with the bottom plate removed. Under these conditions, ^{POURING} can be closely controlled and observed eliminating the possibility of voids in the shielding. All areas inspected by the gamma probing process in which the radiation level indicates a 5% or greater loss in shielding thickness will be further inspected in detail, evaluated to determine effect on overall shield adequacy and a report with recommended repair procedure, if required, submitted for approval.

MECHANICAL FIT OF MATING PARTS

All components will be dimensionally inspected in the normal Quality Control coverage of the equipment. Specific emphasis will be placed on proper fits in the following areas:

- (a) Fuel basket in cask
- (b) Adapters in Fuel Basket
- (c) Piqua dummy fuel assembly in basket
- (d) Elk River dummy fuel assembly in adapter
- (e) Closure head to cask body

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- (f) Lifting yoke to cask
- (g) Cask to cask dolly
- (h) Cask to shipping structure

The required dummy fuel assemblies and cask dolly will be supplied by COO-AEC for the test program.

HYDROSTATIC TEST

The assembled cask and closure head will be subjected to 100 Psi Hydrostatic Test to demonstrate adequate structural strength and leak tightness. The pressure will be transmitted to the internal cavity through the rupture disc bottom flange with disc removed so that all valves and fittings, except rupture disc, can be inspected under pressure.

LEAK TEST

Following the Hydrostatic Test the assembled cask and closure head will be leak tested at 5 Psig using air and soap solution. This will demonstrate leak tightness under normal conditions of transport.

THERMAL TESTS

The thermal performance of the cask will be demonstrated by placing 19 electrical heaters in the basket assembly and operating at various power inputs up to the design value. For this test the Elk River fuel adapters will be in place and both adapter and basket temperature will be measured. A test head with required heater and instrumentation penetrations will be used in place of the closure head. The test head will be insulated to simulate actual closure head with respect to heat loss through the head.

Since the cask is shipped normally dry, the primary objective will be to prove adequacy under dry conditions. However, to provide additional data for cooldown operations and possible future use of the cask with liquid coolants, cooldown tests and tests with the cask water-filled will be performed. The objective of the cooldown tests will be to provide data for detailed cooldown procedures. The objective of the wet tests will be to determine decay heat removal capacity of the cask vs. coolant temperature and pressure.

The results of the tests will be combined with analytical calculations to estimate fuel temperatures under design conditions. Based on observed basket and adapter temperatures, fuel temperatures will be recalculated to provide the best possible prediction under dry conditions.

HANDLING TESTS

Upon completion of the cask assembly and lifting yoke, the adequacy of the proposed procedure for handling the cask in the vertical position and

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Piqua-Elk River Reactors
Spent Fuel Shipping Cask

rotating from vertical to horizontal position will be demonstrated. This will be accomplished using the actual cask dolly and lifting yoke.

REVISED