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PIQUA ELK RIVER REACTORS
SPENT FUEL SHIPPING CASK
DESIGN REPORT
KNAPP MILLS INCORPORATED

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PIQUA ELK RIVER REACTORS

SPENT FUEL SHIPPING CASK

DESIGN REPORT

TABLE OF CONTENTS

SECTION I	System Description
SECTION II	Shielding Analysis
SECTION III	Thermal Analysis
SECTION IV	Stress Analysis
SECTION V	Fire Analysis
SECTION VI	Criticality Analysis
SECTION VII	Loading and Unloading Procedures
SECTION VIII	Test Program

PIQUA-ELK RIVER REACTORS

SPENT FUEL SHIPPING CASK

SYSTEM DESCRIPTION

I. GENERAL

The shipping cask system is designed to ship 19 fuel assemblies from both the Piqua and Elk River Reactor plants starting 90 days after reactor shutdown without liquid coolant. Provisions are included for shipment of the cask in a vertical position by rail or truck. The loaded cask weighs 30 tons; the shipping weight of the entire system is approximately 32 tons.

Shielding is designed to limit radiation from the cask to 10 MR/HR at 3 meters from the cask surface and 200 MR/HR on contact with any point on the cask surface. The decay heat removal system is designed to limit maximum fuel cladding temperatures to less than maximum reactor operating temperatures with no coolant other than air in the cask. For this purpose maximum cladding temperatures taken from Reactor data are:

PIQUA 713°F (Ref. AI SD A87-710-1)

ELK RIVER 618°F (Ref. Hazards Report)

Structurally the cask is designed to meet the requirements of 10CFR 72. For complete flexibility, the cask is designed for maximum internal pressure of 100 PSI to provide for possible future operation of the cask with liquid coolant at maximum allowable (10CFR72) pressure of 50 PSI. The cask is also designed such that the basic shield container will withstand the standard one-hour fire (NFPA No. 251) without loss of shielding. The cask system meets the requirements of ICC regulations and a bureau of explosives permit number will be obtained and assigned to the cask.

With respect to criticality, the cask system is safe with a full load of Elk River fuel assemblies. With a full load of Piqua fuel assemblies, preliminary calculations indicate a neutron poison element will be required in the fuel assembly basket.

Loading, unloading and handling features are designed to be compatible with facilities at both reactor plants and the Savannah River reprocessing site. Preliminary handling and loading procedures at the reactor site and cooldown and unloading procedures at the reprocessing site have been prepared to assure general compatibility of the cask design in these areas.

REFERENCE:
W-3100

System Description
Piqua-Elk River Spent Fuel Shipping Cask

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Page 1

II. Reference Drawings

The following design drawings describe the cask system. The drawings show types of materials and basic cask construction and are not intended to be shop detail fabrication and machining drawings.

Cask Assembly	F-2055
Closure Head	
Assembly	F-2056
Basket Assembly	F-2057
Shipping structure	F-2058 Sheet 1 of 2
Shipping Structure	F-2058 Sheet 2 of 2

III. Detailed Description

The cask system consists of the Body, Closure Head, Fuel Assembly Basket and Shipping Structure. The basket fits closely within the machined cask cavity and is supported on a machined step at the lower end of the cavity. The closure head is bolted to the cask body with 24 high strength socket head cap screws. Sealing is affected by two neoprene "O" rings set in grooves in the cask body.

a. Cask Body

The cask Body consists of concentric inner and outer shells joined at the top by a $1\frac{1}{4}$ inch stainless steel plate and carbon steel bolting rings. The outer shell is one inch carbon steel; the inner shell is rolled from $\frac{3}{4}$ " 50% stainless steel clad carbon steel. The bottom of the internal cavity is a flanged-only head of one inch-40% stainless clad carbon steel. The outer bottom is a flanged only head of $1\frac{1}{4}$ " carbon steel. The 8 inch Annulus between the inner and outer shells is filled with lead shielding metalurgically bonded to both shells. The 7 inch space between inner and outer bottom heads is also filled with lead. A void is provided inside the outer bottom head radius to allow for lead expansion at normal operating temperatures. Carbon steel cooling fins $1\frac{1}{4}$ " x 3" are welded to the outer shell to improve decay heat removal efficiency. A drain line and drain valve are provided at the bottom of the cask to drain water from the internal cavity. The valve is protected from damage during handling and shipping by a heavy steel box structure which completely surrounds the valve. Four iron-constantan thermocouple assemblies are provided in the cask body to indicate inner shell temperature in the region of maximum temperatures.

Three identical lifting lug assemblies are provided on the cask body; two at the top and one at the bottom. These lugs permit lifting the cask in both vertical and horizontal position. Each lifting lug alone is designed to lift the cask; this permits

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Page 2

tilting the cask from vertical to horizontal position using the lug assembly on the "W" axis. All lifting lug assemblies are detachable to avoid interference problems developing with air-lock dolly and air-lock shell. External carbon steel surfaces are painted to prevent corrosion and facilitate decontamination.

b. Closure Head

The Closure Head consists of a flanged and dished head of one inch carbon steel and a stepped bottom plate of $1\frac{1}{4}$ " - 30% stainless steel clad carbon steel. A carbon steel bolting ring is welding to the head and bottom plate to secure the closure head to the cask body. Four dual purpose lifting lug and closure head guide assemblies are bolted to the bolting ring. Two locating pins are also provided in the bolting ring. The lifting lug guides provide for approximate positioning of the closure head on cask body; the locating pins provide for close location and orientation after lifting lug guides have guided head on cask body. The lifting lugs also provide feet for placing the closure head on floor during loading and unloading operations.

An accessory cavity is provided in the top of the closure head by a one inch flanged only stainless steel head. The space between bottom plate, outer head and accessory cavity is filled with lead shielding. The shape of the closure head provides a minimum of 8 inches equivalent lead shielding in any direction from any point on the radioactive sources. A void space is provided at the intersection of accessory cavity and outer head to allow for lead expansion at normal operating temperatures.

A rupture disc assembly (100 PSI) and vent valve are mounted in the accessory cavity. The rupture disc prevents excessive pressure in the cask under extreme accident conditions (fire accident). The vent valve is required during loading cool-down and unloading operations. These assemblies are bolted to the closure head and sealed with neoprene "O" rings set in grooves in the assemblies. The accessory cavity is covered by a flush mounted cover plate to protect the rupture disc and vent valve from damage during handling and shipping.

c. Fuel Assembly Basket

The Basket consists of an aluminum casting in which 19-5.280" cavities are machined. The outside diameter is also machined to closely fit the cask cavity. The basket casting will be Alloy 356-t6 or 43 depending on foundry preference. Both alloys have excellent properties for this application. Investigation of the feasibility of adding a neutron poison element to the basket casting alloy to provide the required safety margin with respect to criticality is currently in progress. Upper and lower adapter plates are attached to the basket to ship Elk River fuel assemblies. To ship Piqua fuel assemblies, bottom corner protector plate segments are all that is required.

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Page 3

The basket diameter is designed so that the differential expansion between the basket and cask will close the cold clearance gap and develop contact between basket and cask as the basket approaches equilibrium temperature after draining water from the cask. This efficiently transfers heat from the basket to the cask wall thus minimizing temperature gradients and reducing fuel temperatures. This system has been proven by dry thermal tests on previous cask designs. The system is self-regulating, since increasing basket temperature increases contact pressure which in turn improves heat transfer.

d. Shipping Structure

The Shipping Structure consists of a base weldment of structural steel shapes and two "A-frame" vertical supports in the fore-and-aft (direction of travel) axis of the cask. The "A-Frame" braces bolt to the cask bolting ring and corners of the base weldment to provide lateral support to the top of the cask in all directions. Lateral support of the bottom of the cask is provided by a ring on the cask bottom head which mates with a ring on the base weldment. The cask weight is normally carried by the center structure of the base weldment. Holes are provided in the base weldment side members for attaching shipping structure to rail car or truck bed.

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Page 4

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 - YEARS	> 2	> 2
LOAD FACTOR	60%	80%
FUEL ASSEMBLY COOLING TIME - DAYS	90 (MIN)	90 (MIN)
RADIAL PEAKING FACTOR	1.47	1.4
AXIAL PEAKING FACTOR	1.47	1.4
FUEL ASSEMBLIES PER CASK	85	148
ACTIVE LENGTH OF FUEL	55"	60"
ACTIVE CORE DIAMETER	58.2"	60"
REF DWGS	7537-71801	12D0200

NOTES:

1. PIQUA DATA FROM AI SD NO. A87-710-1
AND USNRC FORM 434 DATED 7/8/60
2. ELK RIVER DATA FROM PHYSICS REPORT DATED
5/23/60 AND USNRC FORM 434 DATED 7/8/60

REFERENCE:
W-3100

PIQUA-ELK RIVER SPENT FUEL SHIPPING CASK

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SHIELDING
ANALYSIS

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PAGE 1

II. POWER DENSITY CALCULATION

$$\text{PIQUA} \frac{(45.5 \times 10^6)}{(85)(5.210)^2 \frac{\pi}{4} (53)(2.54)^3} = 28.9 \text{ w/cm}^3$$

$$\text{ELK RIVER} \frac{(58.2 \times 10^6)}{(148)(3.450)^2 (60)(2.54)^3} = 33.5 \text{ w/cm}^3$$

CONSIDER PEAKING AND LOAD FACTORS

$$\text{PIQUA} (28.9)(1.47)(1.47)(60\%) = 37.5 \text{ w/cm}^3$$

$$\text{ELK RIVER} (33.5)(1.4)(1.4)(80\%) = 52.5 \text{ w/cm}^3$$

ELK RIVER CASE WILL PROBABLY BE LIMITING.

III. GAMMA SOURCE & SPECTRUM CALCULATION - ELK RIVER

USE PERKINS & KING DATA FOR INFINITE REACTOR OPERATION AND 90 DAYS COOLING

$$S_v = \left(\frac{\text{MEV}}{\text{SEC-WATT}} \right) (\text{POWER DENSITY - w/cm}^3) \div \left(\frac{\text{AVG MEV}}{\text{PHOTON}} \right) = \frac{\text{PHOT}}{\text{CM}^3\text{-SEC}}$$

GROUP	MEV/SEC-WATT	w/cm ³	MEV/γ	S _v -γ/cm ³
I	1.6 × 10 ⁸	33.5	0.4	1.34 × 10 ¹⁰
II	1.15 × 10 ⁹		0.8	4.81 × 10 ¹⁰
III	6.9 × 10 ⁸		1.3	1.78 × 10 ¹⁰
IV	9.5 × 10 ⁷		1.7	1.87 × 10 ⁹
V	1.3 × 10 ⁷		2.0	2.18 × 10 ⁸
VI	1.7 × 10 ⁷		2.5	2.28 × 10 ⁸

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PAGE 2

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 WILL BE CALCULATED AND THESE RESULTS USED TO ESTIMATE SHIELD THICKNESSES FOR VARIOUS ARRANGEMENTS OF FUEL ASSEMBLIES.

NEGLECT SELF-ABSORPTION IN INDIVIDUAL FUEL ASSEMBLIES AND CONVERT VOLUME SOURCE STRENGTH TO LINE SOURCE STRENGTH.

<u>GROUP</u>	<u>$S_V - \gamma/\text{CM}^3\text{-SEC}$</u>	<u>$S_L - \gamma/\text{CM}$</u>
I	1.34×10^{10}	1.03×10^{12}
II	4.81×10^{10}	3.69×10^{12}
III	1.78×10^{10}	1.37×10^{12}
IV	1.87×10^9	1.43×10^{11}
V	2.18×10^8	1.67×10^{10}
VI	2.28×10^8	1.75×10^{10}

EQUATION FOR THE FLUX FROM A LINE SOURCE

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

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PAGE 3

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

$$\theta = \tan^{-1} \frac{30}{133} = 12.7^\circ$$

$$\theta' = \tan^{-1} \frac{30}{15} = 63.4^\circ$$

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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PAGE 4

$$D_c = 10 \left(\frac{133}{15} \right) \left(\frac{6 \times 10^{-6}}{3.5 \times 10^{-6}} \right) = 152 \text{ MR/HR}$$

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 $t = 20.3 \text{ CM}$

GROUP	μ_{PB}	b	B	S_L	$F(\theta, b)$	K_E	Dose - MR/HR
I	2.7	54.8	5.0	1.03×10^{12}	-	-	-
II	1.1	22.3	5.0	3.69×10^{13}	3.8×10^{-11}	1.6×10^{-3}	5.3×10^{-4}
III	0.68	13.8	5.0	1.37×10^{12}	2.0×10^{-7}	2.1×10^{-3}	1.36
IV	0.56	11.4	5.0	1.43×10^{11}	2.3×10^{-6}	2.6×10^{-3}	2.02
V	0.51	10.3	5.0	1.67×10^{10}	7.0×10^{-6}	3.1×10^{-3}	.85
VI	0.48	9.75	5.0	1.75×10^{10}	1.2×10^{-5}	3.6×10^{-3}	1.79
TOTAL							6.02 MR/HR

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PAGE 5

* ASSUME $9\frac{1}{2}''$ 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	1.37×10^{12}	1.45×10^{-8}	2.1×10^{-3}	0.11
IV	13.5	5.7	1.43×10^{11}	2.7×10^{-7}	2.6×10^{-3}	0.27
V	12.3	5.8	1.67×10^{10}	9.1×10^{-7}	3.1×10^{-3}	0.13
VI	11.6	5.9	1.75×10^{10}	1.8×10^{-6}	3.6×10^{-3}	0.32
						<u>0.83 MR/HR</u>

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

VI. APPLY RESULTS TO INTERNAL ARRGT'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

P_2

P_1

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

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PAGE 6

DOSE RATE VS. SHIELD THICKNESS
ONE ELX. OVER FUEL ASSEMBLY
 $T_0 = \infty$ $T_s = 90$ OR 75 LOAD FACT-100%
RADIAL & AXIAL PENKING FACTOR=1.0

DOSE RATE - MR/HR

DOSE RATE - MR/HR

SHIELD THICKNESS - INCHES OF LEAD

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

DOSE AT P_1 - ASSUME 8" Pb EQUIV. SHIELD

<u>FUEL ASSY</u>	<u>AL THICK</u>	<u>LEAD THICK</u>	<u>EQUIV LEAD*</u>	<u>DOSE RATE†</u>
c	1"	8"	8.22	4.6
b	1½	8.6	8.93	1.75
d	1½	8.6	8.93	1.75
a	3½	9.8	10.57	.21
e	3½	9.8	10.57	.21
h	2.7	8.1	8.69	2.6
i	4½	8.25	9.24	1.15
g	5¼	8.5	9.65	.68
TOTAL				12.95 MR/HR

DOSE AT P_2

c	1.15	8.17	8.42	3.5
d	1.15	8.17	8.42	3.5
b	2.25	9.1	9.6	.73
e	2.25	9.1	9.6	.73
a	5.4	10.25	11.44	.1
f	5.4	10.25	11.44	.1
h	2.15	8.15	8.62	2.7
i	2.15	8.15	8.62	2.7
g	12	8.5	11.14	.1
j	12	8.5	11.14	.1

* AL 22% EFFECTIVE AS LEAD

† FROM CURVE PAGE 7

14.26 MR/HR

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PAGE 8

DOSE AT P_2 IS LIMITING. APPLY PEAKING AND LOAD FACTORS FOR TOTAL DOSE RATE
USE A FACTOR OF 1.96 FOR COMBINED RADIAL AND AXIAL PEAKING FACTOR AND 80% FOR LOAD FACTOR.

$$\text{OVERALL FACTOR} = 80\% (1.96) = 1.57$$

$$D_T = (1.57)(14.26) = 22.3 \text{ MR/HR}$$

TRY 8 1/2" EQUIVALENT LEAD SHIELD

DOSE AT P_2

<u>FUEL ASSY</u>	<u>AL THICK</u>	<u>LEAD THICK</u>	<u>EQUIV. LEAD</u>	<u>DOSE RATE</u>
c	1.15	8.67	8.92	1.8
d	1.15	8.67	8.92	1.8
b	2.25	9.67	10.16	.35
e	2.25	9.67	10.16	.35
a	5.4	10.83	12.02	—
f	5.4	10.83	12.02	—
h	2.15	8.67	9.14	1.3
i	2.15	8.67	9.14	1.3
g	12	9.0	11.64	—
j	12	9.0	11.64	—
TOTAL				6.90 MR/HR

$$D_T = (1.57)(6.9) = 10.8 \text{ MR/HR}$$

8 1/2" EQUIVALENT LEAD SHIELD WILL BE ADEQUATE FOR 19 ELK RIVER ASSEMBLIES

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PAGE 10

CHECK PIQUA CASE

USING DATA ON PAGE 2 COMPARE RELATIVE LINE
SOURCE STRENGTH OF PIQUA & ELK RIVER ELEMENTS

$$\text{PIQUA } (37.5 \text{ W/CM}^3) \left(5.210^2 \frac{\pi}{4} \right) = 800$$

$$\text{ELK RIVER } (52.5 \text{ W/CM}^3) (3.450^2) = 625$$

THIS MEANS THAT, NEGLECTING DIFFERENCES IN
SELF-ABSORPTION BETWEEN ELEMENTS, THE PIQUA
SOURCE STRENGTH IS $\frac{800}{625} = 1.28$ TIMES THAT
OF ELK RIVER AND THE DOSE RATE WITH
19 PIQUA ASSEMBLIES AND $8\frac{1}{2}"$ LEAD WILL BE

$$(1.28)(10.8) = 13.8 \text{ MR/HR}$$

FROM CURVE PAGE 7 INCREASING LEAD SHIELD
FROM $8\frac{1}{2}"$ TO $8\frac{3}{4}"$ WILL REDUCE DOSE
RATE $\frac{2.25}{3.15} = 71.5\%$

$$(71.5\%)(13.8) = 9.87 \text{ MR/HR} \quad \text{OK.}$$

→ USE $8\frac{3}{4}"$ EQUIVALENT LEAD SHIELD RADIIALLY ←

THE CONSERVATIVE ASSUMPTIONS IN THESE CALCULATIONS,
NAMELY, NEGLECTING SELF-ABSORPTION, COMBINING PEAKING
FACTORS AND USING DATA FOR INFINITE REACTOR
OPERATION PROVIDE ADEQUATE SAFETY FACTOR.

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PAGE 11

VII TOP & BOTTOM SHIELDING MODEL

CONSIDER A CYLINDRICAL SOURCE EQUIVALENT TO 19 ELK RIVER ASSEMBLIES AND A SLAB SHIELD DIRECTLY ABOVE THE CYLINDER. THIS WILL BE A CONSERVATIVE MODEL OF THE ACTUAL CASE. THE ACTUAL CASE OF 19 ASSEMBLIES IN A SOLID ALUMINUM BASKET WOULD BE MORE CLOSELY APPROXIMATED BY 19 COLLIMATED BEAMS EMANATING VERTICALLY FROM THE BASKET WITH A WEAKER COMPONENT OF RADIATION IN ALL DIRECTIONS ATTENUATED BY THE ALUMINUM BASKET MATERIAL. THIS ACTUAL CASE CANNOT BE DESCRIBED ANALYTICALLY WITHOUT COMPUTER METHODS WHICH ARE NOT JUSTIFIED FOR THIS CASK DESIGN. SHIELD THICKNESSES BASED ON THE 19 ELK RIVER ELEMENTS WILL BE ADEQUATE FOR THE PIQUA ASSEMBLIES BECAUSE OF THE LOWER POWER-DENSITY AND ALSO BECAUSE THE PIQUA ACTIVE FUEL HEIGHT IS 12" DEEPER IN THE SOLID ALUMINUM BASKET WHICH INCREASES BOTH DISTANCE AND COLLIMATION.

DETERMINE EQUIV HOMOGENIZED CYLINDER RADIUS

CONSIDER FUEL PINS OF 19 ASSEMBLIES ON $\frac{3}{4}$ " PITCH

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

DETERMINE FRACTIONS OF UO_2 & SST AND CALCULATE EFFECTIVE SELF-ABSORPTION COEFFICIENTS.

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PAGE 12

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

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

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

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

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

GROUP	<u>UO₂</u>			<u>SST</u>			<u>TOTAL</u>
	<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 TAC 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 $a_1 = \text{APPROX } 19''$

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

$$\theta = \tan^{-1} \frac{23.4}{54.8} = 3.85^\circ$$

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

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Page 13

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

$$\phi = \frac{B S_v \pi R_o^2}{\mu_s} \frac{e^{-b_1}}{4 \pi a^2} K_E = \frac{R_o^2 B S_v e^{-b_1}}{4 a^2 \mu_s} K_E$$

VIII SHIELD CALCULATION

ASSUME 8" Pb = 20.3 CM

GROUP	b	B	S _v	μ _s	e ^{-b₁}	K _E	DOSE RATE
III	13.8	5	1.78 × 10 ¹⁰	.157	1 × 10 ⁻⁶	2.1 × 10 ⁻³	1.34
IV	11.4	5	1.87 × 10 ⁹	.129	1.1 × 10 ⁻⁵	2.6 × 10 ⁻³	2.24
V	10.3	5	2.18 × 10 ⁸	.118	3.35 × 10 ⁻⁵	3.1 × 10 ⁻³	1.08
VI	4.75	5	2.28 × 10 ⁸	.110	5.8 × 10 ⁻⁵	3.6 × 10 ⁻³	2.45
TOTAL							7.21 mR/hr

ASSUME 7" Pb = 17.75 CM

GROUP	b	B	S _v	μ _s	e ^{-b₁}	K _E	DOSE RATE
III	12.05	4.6	1.78 × 10 ¹⁰	.157	5.8 × 10 ⁻⁶	2.1 × 10 ⁻³	7.18
IV	9.95	4.5	1.87 × 10 ⁹	.129	4.8 × 10 ⁻⁵	2.6 × 10 ⁻³	9.25
V	9.05	4.5	2.18 × 10 ⁸	.118	1.2 × 10 ⁻⁴	3.1 × 10 ⁻³	3.49
VI	8.52	4.5	2.28 × 10 ⁸	.110	2.1 × 10 ⁻⁴	3.6 × 10 ⁻³	7.97
TOTAL							27.99 mR/hr

PLOT STRAIGHT LINE ON SEMI-LOG PAPER

REFERENCE:

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Page 14

DOSE RATE - MR/HR

10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0

DOSE RATE VS. SHIELD THICKNESS
 19 ELIC RIVER FUEL ASSEMBLIES
 $T_0 = 10$ $T_2 = 90$ DAYS LOG FACTOR = 100%
 RADIAL & AXIAL PEAKING FACTORS = 1.0

300
250
200
150
100

ON-CONTACT

3 METERS

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 1.4. THIS GIVES A COMBINED PEAKING FACTOR OF .42. 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 80%, THIS LEAVES AN OVERALL FACTOR OF 0.8 TO APPLY TO THE CURVE ON PAGE 15. AND THE INDICATED SHIELD THICKNESS FOR 10 MR/HR @ 3 METERS = 7.6"

CHECK THIS SHIELD THICKNESS FOR 200MR/HR ON CONTACT USING EQUATION PAGE 13.

GROUP	b	B	Sv	M _s	E _{FUNCTION}	K _E	DOSE/HR
III	13.1	4.9	1.78×10^{10}	.157	1.12×10^{-7}	2.1×10^{-3}	65.3
IV	10.8	4.8	1.87×10^9	.129	1.21×10^{-6}	2.6×10^{-3}	109.1
V	9.85	4.8	2.18×10^8	.118	3.23×10^{-6}	3.1×10^{-3}	44.4
VI	9.26	4.7	2.28×10^8	.110	6.17×10^{-6}	3.6×10^{-3}	108.2
TOTAL							327.0

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PAGE 16

THIS RESULT INDICATES THE ON CONTACT DOSE RATE IS 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	1.78×10^{10}	.157	5.43×10^{-8}	2.1×10^{-3}	32.3
IV	11.4	5	1.87×10^9	.129	6.51×10^{-7}	2.6×10^{-3}	61.4
V	10.3	5	2.18×10^8	.118	2.04×10^{-6}	3.1×10^{-3}	29.2
VI	9.75	5	2.28×10^8	.110	3.65×10^{-6}	3.6×10^{-3}	68.0
							<u>190.9</u> MR/HR

PLOT ON-CONTACT CURVE ON PAGE 15.

CONSIDERING LOAD FACTOR OF 80% INDICATED SHIELD THICKNESS IS 7.8" OF LEAD

X BOTTOM SHIELDING

AT THE BOTTOM OF THE CORE THE AXIAL PEAKING FACTOR IS APPROX. 0.6. THE RADIAL PEAKING FACTOR IS STILL 1.4 GIVING A COMBINED FACTOR OF .84. TO ALLOW FOR SHARP UP-TURN IN AXIAL PEAKING FACTOR USE AN OVERALL PEAKING FACTOR OF 1.25 AND A POWER FACTOR OF 80% GIVING A FACTOR OF 1.0 ON ON-CONTACT CURVE PAGE 15. INDICATED SHIELD THICKNESS IS 7.96". USE 8" EQUIVALENT LEAD

REFERENCE:

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PAGE 17

XI RADIATION LEVEL AT BOLTING RING

THE SRP REPROCESSING FACILITY REQUIRES THAT PERSONNEL RECEIVE NO MORE THAN 25 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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PAGE 18

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 :

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

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

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

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

$$a_2 = 133''$$

$$a_3 = 30''$$

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

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

EVALUATE FOR 8 ³/₄" LEAD SHIELD AND

$$D_{P_2} = 10 \text{ MR/HR}$$

$$D_{P_3} = (10)(1.25)(2.22) \left[\frac{(3.55 \times 10^{-6}) - (2.82 \times 10^{-6})}{(2.05 \times 10^{-6})} \right] = \underline{\underline{9.9 \text{ MR/HR}}}$$

THIS INDICATES EACH MAN MAY SPEND 2 1/2 HRS IN REMOVAL OF CLOSURE HEAD BOLTS AND ATTACHMENT OF LIFTING LUGS AND ACCESSORIES. THIS TIME INTERVAL IS CONSIDERED ADEQUATE.

REFERENCE:

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DRAWING NO.

PAGE 19

PIQUA-ELK RIVER REACTORS SPENT FUEL SHIPPING CASK THERMAL ANALYSIS

I BASIC DATA

<u>ITEM</u>	<u>PIQUA</u>	<u>ELK RIVER</u>
REACTION POWER - WATTS	45.5×10^6	58.2×10^6
OPERATING TIME - YEARS	> 2	> 2
LOAD FACTOR	60%	80%
FUEL ASSY COOLING TIME - DAYS	90 (MIN)	90 (MIN)
RADIAL PEAKING FACTOR	1.47	1.4
AXIAL PEAKING FACTOR	1.47	1.4
FUEL ASSEMBLIES PER CORE	85	148
ACTIVE LENGTH OF FUEL	53"	60"
ACTIVE CORE DIAMETER	58.2"	60"
REF DWGS	7537-71801	12D02000

NOTE 3:

1. PIQUA DATA FROM AI SD NO. A87-710-1
AND USNRC FORM 434 DATED 7/8/60
2. ELK RIVER DATA FROM PHYSICS REPORT
DATED 5/23/60 AND USNRC FORM 434
DATED 7/8/60

REFERENCE:
W-3100

PIQUA-ELK RIVER SPENT FUEL SHIPPING CASK

DRAWING NO.

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THERMAL
ANALYSIS

PAGE 1

II DECK HEAT (CALCULATIONS)

USE PERIOD 4 KING DOWN FOR TURBINE REACTION OPERATIONS AND 30 LATS COOLING

$$\text{TOTAL } \gamma \text{ ENERGY} = 2.3 \times 10^3$$

$$\text{TOTAL } \gamma \text{ ENERGY} = 2.0 \times 10^3$$

$$4.3 \times 10^3 \frac{\text{MEV}}{\text{SEC}} \text{ PER UNIT POWER}$$

PIQUIN

$$(4.3 \times 10^3 \frac{\text{MEV}}{\text{SEC}}) (45.2 \times 10^{-10} \text{ sec}) (10 \times 10^{-10} \frac{\text{WAT}}{\text{MEV}}) = 1300 \text{ W}$$

$$(1300 \text{ WAT}) (3.413 \frac{\text{BTU}}{\text{WAT}}) \div 80 = 1260 \frac{\text{BTU}}{\text{HR}} \text{ AVG ASY}$$

$$\frac{(1260)(14)(14)}{52/12} = 615 \text{ BTU/HR PER FOOT MAX HOT-SPOT}$$

ELK KIVER

$$(4.3 \times 10^3) (58.2 \times 10^{-10}) (16 \times 10^{-10}) (3.413) = 922 \frac{\text{BTU}}{\text{HR}} \text{ AVG ASY}$$

$$\frac{(922)(14)(14)}{5} = 362 \text{ BTU/HR PER FOOT MAX HOT-SPOT}$$

CONV DOWN PLANT LOW REACTOR

$$\text{PIQUIN HOT SPOT} = (615)(0.5) = 307 \text{ BTU/HR PER FOOT}$$

$$\text{ELK KIVER HOT-SPOT} = (362)(8.3) = 2990 \text{ BTU/HR PER FOOT}$$

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PAGE 2

III ANALYTICAL MODEL

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

CASK CROSS-SECTION

LIQUID FUEL ASSEMBLIES WILL BE CRUSHED IN ALUMINUM BASKET DIRECTLY. ROUND TO SQUARE ADAPTERS WILL BE PLACED IN ORDER TO CRUSH ELK RIVER FUEL ASSEMBLIES

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Page 3

IV CALCULATION OF TEMPERATURE DISTRIBUTION - PIQUA

CALCULATE T_1 BASED ON FINNED SURFACE

BASIC EQUATION

$$Q = h_c A_c (T_1 - T_A) + \epsilon \sigma A_R (T_1^4 - T_A^4)$$

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

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PAGE 4

ASSUME $h_c = 0.7$ APPROX

$$N = 0.25 \sqrt{\frac{0.7}{(26)(0.0104)}} = 403$$

$$\eta_F = 95\%$$

$$A_c = 11.1 + .95(37.5) = 46.7 \text{ FT}^2$$

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

$\epsilon = 0.9$ 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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PAGE 5

CALCULATE AND PLOT CURVE OF BASIC EQUATION

For $T_1 = 140^\circ\text{F}$

$$h_c = 0.19 (40)^{1/2} = 0.65$$

$$Q = (0.65)(46.7)(40) + (0.9)(141)(224 - 170) = 1895 \text{ BTU/hr.}$$

For $T_1 = 170^\circ\text{F}$

$$h_c = 0.19 (70)^{1/2} = .78$$

$$Q = (0.78)(46.7)(70) + (0.9)(141)(213 - 170) = 3860$$

For $T_1 = 200^\circ\text{F}$

$$h_c = 0.19 (100)^{1/2} = .88$$

$$Q = (0.88)(46.7)(100) + (0.9)(141)(328 - 170) = 6120$$

PLOT CURVE - PAGE 7

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

$$Q = (19)(1260)(147)(60\%) = 21,100 \text{ BTU/hr.}$$

THE EXTERNAL SURFACE WILL BE FINISHED OVER A HEIGHT OF 7 FEET. ASSUME 6 FEET OF THIS HEIGHT EFFECTIVE FOR HEAT DISSIPATION. THE ACTIVE LENGTH OF PIQUA FUEL IS 53"

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DRAWING NO.

PAGE 6

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

AND AXIAL CONDUCTION OF HEAT IN ALUMINUM BASKET AND CASK WALL WILL EFFECTIVELY DISTRIBUTE HEAT UNIFORMLY OVER THE 6 FOOT HEIGHT. FOR THIS REASON, THE TEMPERATURE DISTRIBUTION AT THE CASK SURFACE WILL NOT BE SIGNIFICANTLY AFFECTED BY AXIAL PEAKING FACTOR.

$$\text{THEN } Q \text{ PER FOOT} = \frac{21100}{6} = 3515 \text{ BTU/HR}$$

FROM CURVE PAGE 7 $T_1 = 165^\circ \text{F}$

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.

$$Q = 369 \text{ BTU/HR PER ASSY PER FOOT (PAGE 2)}$$

$$R_2 = 24"$$

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

$$K = 19$$

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

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Page 8

$$T_2 - T_1 = \frac{(19 \times 369)(\ln 1.63)}{2\pi(1)(19)} = 28.8^\circ\text{F}$$

$$\text{USE } T_2 = \underline{194^\circ\text{F}}$$

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.

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PAGE 9

NEUTRON RADIATION AND CALCULATING $T_2 - T_2$

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

$$Q = 369 \text{ BTU/hr} \times 19 = 7000 \text{ BTU/hr-Ft}$$

$$X = \frac{.010"}{12} = .000833 \text{ Ft}$$

$$K = .018 \text{ @ } 200^\circ\text{F}$$

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

$$\Delta T = \frac{(7000 \times .000833 \times 10^{-4})}{(.018 \times 7.73)} = 46.1^\circ\text{F}$$

$$T_2 = 240^\circ\text{F}$$

CHECK AVAILABLE THERMAL EXPANSION

$$\text{BASKET } (13 \times 10^{-6}) (29.5 \times (240 - 70)) = .065$$

$$\text{SHELL } (6 \times 10^{-6}) (29.5 \times (194 - 70)) = .022$$

$$.043"$$

THIS MEANS A COLD CLEARANCE OF .043" WHICH IS CLOSE BUT FEASIBLE. BASKET, AND CRACK MACHINING TOLERANCES MUST BE CLOSELY CONTROLLED.

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PAGE 10

CALCULATE T_4

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

ASSUME ALL HEAT FROM ASSY b AND $\frac{1}{6}$ OF a FLOWS
RADIALLY THROUGH A SECTION OF ALUMINUM $1\frac{1}{2}$ "
(RADIALLY)
THICK AND $6\frac{1}{8}$ " LONG, AND HEAT FROM ASSEYS c
AND d IS UNIFORMLY TRANSFERRED TO THIS SECTION
ALONG THE RADIUS Q_{ab}

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Page 11

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

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

$$Q = 369 + \frac{369}{6} = 430$$

$$Q = (2)(369) = 738$$

$$X = 0.51$$

$$X = 0.51$$

$$K = 85$$

$$K = 85$$

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

$$A = 0.125$$

$$\Delta T_{ab} = \frac{(430)(0.51)}{(85)(0.125)} = 226^\circ\text{F}$$

$$\Delta T_{cd} = \frac{(738)(.51)}{(2)(85)(.125)} = 17.6^\circ\text{F}$$

USE COMBINED $\Delta T = 38^\circ\text{F}$ $T_4 = \underline{\underline{278^\circ\text{F}}}$

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.

$$\Delta T_a = \frac{(61.5)(.5)}{(185)(.062)} = 5.8^\circ\text{F} \quad \Delta T_b = \frac{(369)(0.5)}{(2)(85)(.062)} = 17.5^\circ\text{F}$$

COMBINED $\Delta T = 23^\circ\text{F}$ $T_5 = 301^\circ\text{F}$

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Page 12

CALCULATE FUEL ASSY INTERNAL TEMP

FIN DETAIL

CALCULATE T_6

ASSUME STAGNANT AIR FILM BETWEEN FUEL ASSY CAN AND BASKET .030" THICK. THIS WILL GIVE 1/16" 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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PAGE 13

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

SURFACE 5 IS CLEAN BRIGHT ALUMINUM - $\epsilon_5 = 0.1$

SURFACE 6 IS DARKENED SST WHICH HAS BEEN EXPOSED TO ORGANIC COOLANT AT 550 °F FOR GREATER THAN 2 YEARS - $\epsilon_6 = .55$

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

$$Q = 369 \text{ BTU/Hr PER FOOT}$$

$$K = .021 @ 325^\circ\text{F}$$

$$X = \frac{.030}{12} = .0025 \text{ FT}$$

$$\text{TRY } T_6 = 330^\circ\text{F}$$

$$Q = (8.4)(1.36)(29) + (.092)(1.36)(674 - 577) = 343 \text{ BTU/Hr}$$

$$\text{TRY } T_6 = 335^\circ\text{F}$$

$$Q = (8.4)(1.36)(34) + (.092)(1.36)(692 - 577) = 402$$

$$\text{TRY } T_6 = 332$$

$$Q = (8.4)(1.36)(31) + (.092)(1.36)(681 - 577) = 367 \text{ OIL}$$

$$T_6 = 332^\circ\text{F}$$

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Page 14

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 FINS.

AREA EFFECTIVE FOR RADIATION IS A
FUNCTION OF FIN TIP RADIUS

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

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

$$E' = \frac{1}{\frac{1}{E_7} + \frac{1}{E_6} - 1}$$

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. - $E_7 = 0.2$

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

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PAGE 15

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

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

$$4r = .175$$

$$r = .0438$$

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

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

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

$$T_{RY} \quad T_f = 415^\circ\text{F} \quad K = .022 @ 375^\circ\text{F}$$

$$Q = \frac{.022}{.008} (1.31 \times 83) + (.022 \times 1.34)(1015 - 681) = 376 \text{ BTU/hr}$$

$$T_{RY} \quad T_f = 414^\circ\text{F}$$

$$Q = \frac{.022}{.008} (1.31 \times 82) + (.022 \times 1.34)(1010 - 681) = 371 \text{ BTU/hr OK}$$

$$T_f = \underline{\underline{414^\circ\text{F}}}$$

REFERENCE:

DRAWING NO.

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

Page 16

CALCULATE T₈

NEGLECT TEMPERATURE GRADIENT THROUGH FUEL CYLINDER AND ASSUME FINS ON INSIDE OF OUTER FUEL CYLINDER AT 398°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)

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

$$R_{m8} = 1.911 + .044 = 1.985''$$

$$\text{MEAN DIST } \bar{X} = .146'' = 0.122 \text{ FT}$$

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

HEAT RELEASE Q_8 IS PROPORTIONAL TO MEAN CIRCUMFERENCE OF CYLINDERS

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

$$\begin{array}{rcl} \text{Circum 8} & = & 3.602 \pi = 11.32 \\ \text{Total} & & 25.87 \end{array}$$

$$Q_8 = \frac{1132}{25.87} \times 369 = 161 \text{ BTU/HK PER FOOT}$$

REFERENCE:

DRAWING NO.

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

PAGE 17

$$\underline{T_{RY} T_8 = 495^{\circ}\text{F}} \quad K = .0235 @ 450^{\circ}\text{F}$$

$$Q = \frac{.023}{.0122} (1.08)(81) + (0.172)(1.08)(1440 - 1010) = 24.5$$

$$\underline{T_{RY} T_8 = 470^{\circ}\text{F}}$$

$$Q = \frac{.023}{.0122} (1.08)(56) + (0.172)(1.08)(1290 - 1010) = 166.$$

$$\underline{T_{RY} T_8 = 469^{\circ}\text{F}}$$

$$Q = \frac{.023}{.0122} (1.08)(55) + (0.172)(1.08)(1285 - 1010) = 163 \text{ BTU/H.} <$$

USE $T_8 = \underline{469^{\circ}\text{F}}$ WHICH IS MAX.

HOT-SPOT FUEL TEMP IN DRY CASE

V CALCULATE TEMP DISTRIBUTION - ELK RIVER

TOTAL HEAT LOAD ON CASK OUTER SURFACE

$$Q_T = (923)(1.4)(19)(80\%) = 19,600 \text{ BTU/Hr}$$

ELK RIVER FUEL ACTIVE LENGTH = 60"

ASSUME 7 FOOT HEIGHT OF CASK EXTERNAL SURFACE EFFECTIVE FOR HEAT DISSIPATION.

$$Q \text{ PER FOOT} = \frac{19,600}{7} = 2800 \text{ BTU/HR}$$

FROM PAGE 7 $T_i = 155^{\circ}\text{F}$

REFERENCE:

DRAWING NO.

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Page 18

USING PREVIOUS CALCULATIONS CORRECT TEMPERATURE DISTRIBUTION FOR ELK RIVER CASE.

ELK RIVER HOT-SPOT = 290 BTU/HR

PIQUA " = 369 "

} PAGE 2

$$\text{FACTOR} = \frac{290}{369} = .785$$

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

$$(T_5 - T_1)_{ER} = .785 (301 - 185) = 107$$

$$T_5 = 107 + 155 = 262^\circ\text{F}$$

ELK RIVER FUEL ASSEMBLY TEMPERATURES

MODEL

LET T_6 = 1ST ROW PINS

T_7 = 2ND ROW PINS

T_8 = CENTER PIN

REFERENCE:

DRAWING NO.

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

PAGE 19

CALCULATE T_6

BASIC EQUATION

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

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

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

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 . $T_f = 425^\circ\text{F}$

$$\text{AVG } X \cong 0.7'' = .058 \text{ FT}$$

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

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

RUN TRIAL CALCULATION

$$A_c = A_R = \frac{(3450)(4)}{12} \times 1 = 1.15 \text{ FT}^2$$

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

REFERENCE:

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DRAWING NO.

Page 20

$$\epsilon_6 = 0.7$$

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 $T_6 = 600^\circ\text{F}$

$$Q = (48 \times 1.15)(600 - 262) + (.096 \times 1.15)(2180 - 470)$$

$$= 1861 + 189 = 375 \text{ BTU/hr}$$

TRY $T_6 = 550^\circ\text{F}$ USE $h'_c = 0.45$

$$Q = (.45 \times 1.15)(288) + (.096)(1.15)(1800 - 470)$$

$$= 149 + 147 = 296 \text{ BTU/hr} \quad \text{OK.}$$

THIS PRELIMINARY CALCULATION INDICATES
IT IS FEASIBLE TO CARRY ELK RIVER FUEL
ASSEMBLIES WITHOUT ADAPTERS AND STILL
NOT EXCEED MAXIMUM ALLOWABLE CLADDING
TEMPERATURES. REFINE ANALYSIS AND DETERMINE
CLADDING TEMPERATURE OF CENTER FUEL PIN

DETERMINE AVERAGE DISTANCE X FROM FIRST
ROW OF TUBES TO ALUMINUM BASKET SURFACE

$$\text{AREA HOLE} = 5.270^2 \frac{\pi}{4} = 21.8 \text{ IN}^2$$

$$\text{AREA ASSY} = 3.450^2 = \frac{11.9}{9.9} \text{ IN}^2$$

REFERENCE:

DRAWING NO.

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PAGE 21

LET: X = AVERAGE DISTANCE

D = HOLE DIA IN BASKET = 5.270

$$\left[D^2 - (D - 2X)^2 \right] \frac{\pi}{4} = 9.9$$

$$-X^2 + DX - 3.15 = 0$$

$$X = .685" = .057 \text{ FT}$$

$$\text{For } T_b = 550^\circ\text{F} \quad T_f = \frac{550 + 262}{2} = 406^\circ\text{F}$$

$$h'_c = \left(\frac{.0225}{.057} \right) \left(\frac{.020}{1.64} \right) \left[(.057)^3 (1.74 \times 10^5) (288) \right]^{\frac{1}{4}} = .47$$

$$Q = (.47)(1.15)(288) + (.096)(1.15)(1800 - 470) = 303 \text{ BTU/hr}$$

$$\text{Try } T_b = 540^\circ\text{F}$$

$$Q = (.47)(1.15)(278) + (.096)(1.15)(1730 - 470) = 289 \text{ OK}$$

$$\text{At } T_b = 540^\circ\text{F} \quad T_f = \frac{540 + 262}{2} = 401^\circ\text{F}$$

$$h'_c = \left(\frac{.0225}{.057} \right) \left(\frac{.020}{1.64} \right) \left[(.057)^3 (1.87 \times 10^5) (278) \right]^{\frac{1}{4}} = .47 \text{ OK}$$

USE $T_b = \underline{540^\circ\text{F}}$ FIRST ROW PIN CLADDING

REFERENCE:

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PAGE 22

FUEL NSSY INTERNAL MODEL

CONSIDER ABOVE CROSS SECTION TO BE MADE UP OF INFINITE PLANES WITH RADIATION FROM PLANE TO PLANE AND CONDUCTION IN STAGNANT AIR

DETERMINE AVERAGE X

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

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

HEAT TRANSFER FROM 2ND ROW TO FIRST ROW IS $\frac{9}{25} \times 290 = 104 \text{ BTU/HR}$

$$A_c = A_r = \frac{1.950 \times 4}{12} \times 1 = .65 \text{ FT}^2$$

$$\epsilon' = \frac{1}{\frac{1}{0.7} + \frac{1}{0.7} - 1} = .538$$

REFERENCE:

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PAGE 23

$$\underline{T_{RY} \quad T_7 = 600^\circ F} \quad T_f = \frac{540+600}{2} = 575^\circ F \quad K = .026$$

$$Q = \left(\frac{.026}{.036} \right) (0.65)(60) + (.54)(.65)(2180-1730)$$

$$Q = 28 + 158 = 186 \text{ BTU/HR TOO HIGH}$$

$$\underline{T_{RY} \quad T_7 = 570^\circ F} \quad T_f = 550^\circ F \quad K = .0255$$

$$Q = \left(\frac{.0255}{.036} \right) (0.65)(30) + (.54)(.65)(1940-1730)$$

$$Q = 14 + 74 = 88 \text{ BTU/HR TOO LOW}$$

$$\underline{T_{RY} \quad T_7 = 575^\circ F} \quad T_f = 557^\circ F \quad K = .0256$$

$$Q = \left(\frac{.0256}{.036} \right) (.65)(35) + (.54)(.65)(1980-1730)$$

$$Q = 16.2 + 87.6 = 104 \text{ BTU/HR OK}$$

$$\text{USE } T_1 = \underline{575^\circ F}$$

Calculate T_8

$$A_c = A_R = \frac{450 \pi}{12} \times 1 = .118 \text{ FT}^2$$

$$Q = \frac{1}{25} \times 290 = 11.6 \text{ BTU/HR}$$

NEGLECT CONDUCTION

$$\underline{T_{RY} \quad 600^\circ F}$$

$$Q = (.54)(.118)(2180-1980) = 12.8 \text{ BTU/HR}$$

$$T_8 = \underline{600^\circ F} \quad \text{MAX CLADDING TEMP DRY}$$

REFERENCE:

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DRAWING NO.

Page 24

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

VI ESTABLISH BASKET DIAMETER (REF PAGE 9,10)

PREVIOUS CALCULATIONS INDICATE AN AVERAGE BASKET TEMPERATURE OF APPROX 270°F
 CALCULATE DIFFERENTIAL EXPANSION AVAILABLE BETWEEN BASKET AND SHELL (SHELL TEMP 194°F).
 USE NOMINAL 30" INCH DIAMETERS.

$$\begin{aligned} \text{BASKET } (13 \times 10^{-6})(30)(270-70) &= 0.078 & \text{ALLOY 356-T6} \\ \text{SHELL } (6 \times 10^{-6})(30)(194-70) &= 0.022 \\ & \underline{0.056"} \end{aligned}$$

THIS MEANS A COLD CLEARANCE OF .056" CAN BE ALLOWED

FINAL DIAMETERS

$$\begin{aligned} \text{CASK} & 30.000 \pm .005 \\ \text{BASKET} & 29.944 \pm .005 \end{aligned}$$

THE ASSUMPTION OF .010" AIRGAP ON PAGE 9 IS ADEQUATE TO COVER THE $\pm .005$ TOLERANCES ON BOTH DIMENSIONS.

REFERENCE:

DRAWING NO.

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Page 25

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	469°F	301°F	385°F
Elk River	600°F	262°F	431°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 THE 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 431°F FOR ELK RIVER CASE. SINCE THIS IS BASED ON THE HOT-SPOT IN THE BASKET IT SHOULD BE CONSERVATIVE.

REFERENCE:

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DRAWING NO.

Page 26

IT IS NOT POSSIBLE TO DETERMINE 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:

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

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

ANALYTICAL MODEL

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

REFERENCE:

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PAGE 27

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

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

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

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

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

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

MARKS PAGE 377

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

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

$$h_c = 0.2(430 - 222)^{1/4} = .76$$

$$Q = (.76)(4.9)(208) = 775 \text{ BTU/HR}$$

T_1 TOO HIGH

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

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

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

$$h_c = 0.2(270)^{1/4} = .81$$

$$Q = (.81)(4.9)(270) = 1070 \text{ BTU/HR}$$

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

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

REFERENCE:

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PAGE 28

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

$$h_c = 0.2 (430 - 147)^{1/4} = .82$$

$$Q = (.82)(4.9)(283) = 1140 \text{ BTU/HR}$$

CLOSE ENOUGH AGREEMENT -

USE $T_1 = 140^\circ\text{F}$, $T_2 = 147^\circ\text{F}$

AVERAGE LEAD TEMP - 145 $^\circ\text{F}$ →

REFERENCE:

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 29

STRESS ANALYSIS

DESIGN CONCEPT.

WEIGHTS OF STEEL, LEAD, ALUMINUM MATERIALS

GEOMETRY AND MEMBER STRESS RATIOS FOR STRUCTURE.

DETAIL STRESS ANALYSIS OF SUPPORT STRUCTURE.

CASK STRESSED AS A SIMPLE BEAM UNDER 10G.

STRUCTURAL INTEGRITY UNDER IMPACT.

PRESSURE VESSEL ANALYSIS FOR 100 PSI.

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 1

W. A. Bachman 2-26-62

DESIGN CONCEPT.

In the course of developing the concept of this cask and of its shipping structure it became apparent that the design desiderata were being secured by "the hard way". This is the usual means by which the maximum number of desirable features can be made compatible with specifications. We believe the following design characteristics are found to be properly integrated.

1. All stresses based on yield points at the required loadings
2. Each of 3 lifting lugs rated at 66 for entire cask assembly
3. Four independent head lifting lugs convenient and provide guidance for under-water handling.
4. All lugs detachable
5. Cask lifting lugs provide easy manipulation in several methods of handling at different installations.
6. Closure head provides recessed protection for valve and rupture disc. This feature could be made to include other controls, as desired.
7. Closure head standard formed section & most rigid under impact.
8. Joint between cask and head provides lateral shear land and is self-draining
9. Knuckle radii for both inner and outer shells reduce local stresses and provide minimum vulnerability in handling and in impact.
10. Shipping structure uses tension-compression struts instead of tension tie members for economy and max. strength.
11. Arrangement of A frame struts is optimum for loading conditions
12. Two A frames are detachable from both cask and platform.
13. Cask sits in horizontal shear ring and is attached by only 8 bolts at two positions at top of A frames.
14. Full 10G dynamic in addition to 1G static loadings.
15. Platform can be independently (and permanently) attached (if desired) to the carrier frame, having a low profile design.

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 2

At-Ba-pm 2-26-62

SUMMARY OF WEIGHTS AND G.G.

	<u>STEEL</u>	<u>LEAD</u>	<u>TOTALS</u>		<u>H "</u> <u>TO CASK</u> <u>BOTTOM</u>	<u>M^{##}</u> <u>PIQUA</u>	<u>M^{##}</u> <u>ELK RIVER</u>
<u>HEAD</u>	2100				97.65	205,065	
		4244			98.24	<u>416,930</u>	
			6344	6344		621,995	
<u>CASK</u>	8300				46.91	389,353	
		38,544			45.75	<u>1,763,388</u>	
			46,844	46,844		2,152,741	
<u>HEAD + CASK</u>	10,400	42,788	53,188	53,188		2,774,736	2,774,736
<u>BASKET</u>			1810	1810	52.	94,120	94,120
<u>FUEL ELEMENTS</u>	(PIQUA-19x250)		4750		52	247,000	
	(ELK RIVER-19x90)			1710	52		88,920
<u>BASKET & ELEMENTS</u>			6560	3520		341,120	183,040
<u>TOTAL CONTAINER</u>			<u>59,748</u>	<u>56,708</u>		3,115,856	2,957,776
		CG. ABOVE CASK BOTTOM	52.15"	52.15"			
<u>SHIPPING STRUCTURE</u>			3500.	3500.			
			<u>63,248</u>	<u>60,208.</u>			

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 3

Of 9 Backing 8-26-62

STEEL WEIGHT & VOLUME CLOSURE HEAD

SECT		VOL IN ³	H IN	MOM.
a	$1 \times \pi 8^2$	201.	18.25	2650
b	$1 \times 1 \times \pi (15)$	47.	11.9	560.
c	$5 \times \pi (9^2 - 8^2) = 5 \left(\frac{254.47}{53.41} \right)$	267	10.8	2880.
d	$1 \times \pi 9^2$	255.	8.25	2100.
e	$(1 \times 15) \times 2\pi/16$	1570.	10.3	15,520.
f	$4 \times \pi (24^2 - 23^2) = 4 \left(\frac{1809.56}{147.65} \right)$	590.	5.6	3300.
g	$1 \frac{1}{8} \times \pi (24^2 - 15^2) = 1.125 \left(\frac{1809.56}{1102.70} \right)$	1240.	3.	3720
h	$4.75 \times \pi \left[\left(\frac{30}{2} \right)^2 - \left(\frac{27 \frac{1}{4}}{2} \right)^2 \right] = 4.75 \left(\frac{706.86}{123.16} \right)$	586.	1.75	1027.
i	$1 \frac{1}{8} \times \left(\frac{27 \frac{1}{4}}{2} \right)^2 \pi = 1.125 (583.70)$	657.	.6	396.
k	$3 \frac{1}{2} \times \pi (26^2 - 24 \frac{1}{16}^2) = 35 \left(\frac{2123.72}{304.72} \right)$	1069	3.6	3860.
		6422		36013.
LOGS - item (9)	(4) $(9 \times 4 + 9 \times 5) 1 \frac{1}{2} = 6 \times 81$	486	5.3	2580.
	(16) $(1 \frac{1}{2} \times 3 \frac{1}{2} \times 1 \frac{3}{4}) = 140$	140	4.8	672.
		7048 m ³		39265

$$\text{C.G. AT } \frac{39265}{7048} = 5.571''$$

$$\text{WT} = 7048 \times .284 = 2002. \#$$

$$\text{ALLOW MISCL} = 98.$$

$$\text{TOTAL WEIGHT} = 2100 \#$$

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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PAGE 4

W. A. Backus 2-26-62

LEAD WEIGHT & VOLUME CLOSURE HEAD.

SECT	IN^3 VOLUME	IN H	IN^4 MOMENT
a 4" fillet $(.2146 R^2)(5 + .7766 R) 2\pi$ $= .2146 \times 16 \times 8.1064 \times 2\pi =$	175.	7.63	1338.
b $3 \frac{3}{8} \frac{\pi}{4} (25^2 - 18^2) = 10.6 \times 75.75 =$	797	8.43	6730.
c $\frac{20 \frac{3}{8} - 12.5}{2} (3.375) 2\pi (12.5 + \frac{7.875}{3})$ $= \frac{7.875}{2} 3.375 (2\pi) 15.125 =$	1262	7.87	9940
d $\frac{1}{4} \times \pi (20.75)^2$	339	6.62	2245
e $3 \times \pi (20)^2$	3770	5.	18,850
f $.7854 (3)^2 2\pi (20 + 3 \times .7766)$ $= .7854 (18\pi) (22.3298) =$	995	4.77	4750
g $\frac{7}{8} \times \pi (23)^2$	1453	3.06	4450
h $2 \frac{5}{8} \times \pi (13.75)^2 = 2.62 \times 593.957 =$	1560	1.312	2062
Net Vol. = $\frac{10,351 \text{ in}^3}{50,365}$			
C.G. at $\frac{50,365}{10,351} = 4.866$ " to bottom lead.			
Weight = $10351 \times .41 = 4244$ #			

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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PAGE 5

By A. B. B. 2-26-62

STEEL WEIGHT AND VOLUME - CASK.

DWG. F-2055

ITEM NO.		VOL.	H	MM.
5	$1\frac{1}{4} \pi (24.5^2 - 15^2) = 1.25 (1885.74 - 706.86)$ $= 1.25 (1178.88) =$	1472	92.37	135,968
3	$73\frac{1}{8} \pi (15.5^2 - 15^2) = 73.125 (754.77 - 706.86)$ $= 73.125 (47.91) =$	3500	55.75	195,000
4	$5\frac{3}{8} \pi (15.5^2 - 14.5^2) = 5.375 (754.77 - 660.52)$ $= 5.375 (94.25) =$	507	15.	7,610
	$.7854 (4^2 - 3^2) 2\pi (14.3) = .7854 (7) 2\pi (14.3) =$	594	9.75	5,780
	$1 \times \pi (11.5)^2 =$	415.48	8.75	3,630
6	$2\frac{1}{2} \pi (26^2 - 23\frac{1}{2}^2) = 2.5 (2,123.72 - 1734.94)$ $= 2.5 (388.78) =$	972.	91.4	88,000
7	$80\frac{1}{4} \pi (24.5^2 - 23.5^2) = 80.25 (1885.74 - 1734.94)$ $= 80.25 (150.80) =$	12,100	51.25	621,000
8	$6 \pi (24.5^2 - 23.25^2) = 6 (1885.74 - 1698.22)$ $= 6 (187.52) =$	1125	8.	9,000
	$.7854 (5^2 - 3.75^2) 2\pi (23) = .7854 (10.94) 46\pi =$	1124	1.6	1,800
9	$1\frac{1}{4} \pi (19.5^2) = 1.25 (1194.59) =$	1493	.625	935
10	$3/4 \pi (21^2 - 19.5^2) = .75 (1385.44 - 1194.59)$ $= .75 (190.85) =$	143	- 3/8	} - 62
11	$3/4 \pi (3)^2 = .75 (28.274) =$	21	- 3/8	
13	$72 \text{ fins } 1/4 \times 3 \times 78.75 = 72 \times .75 \times 78.75 =$	4250	46.25	196,500
27-28	$1/8 \times 1 \times \pi \times 47 \times (2) = .25 \pi 47$	37	88.8	3,290
22	③ $\times 90 \times 3$	810	77. (down)	62,300
	⑥ $\times 20 \times 2$	240	85.	20,400
		28,803 m ³		1,351,151
		$\times .284$		
		8180.05 #		
		120.		
		8300. #		
				C.G = $\frac{1,351,151}{28,803}$
				= 46.91 "

Add miscel.

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 6

of 1 Backus 2-26-62

LEAD WEIGHT & VOLUME CASK.

SECT.		VOL.	H	MOM.
a	$85.25 \pi [(23.5)^2 - (15.5)^2]$ $= 85.25 \left(\frac{1734.94}{980.17} \right) =$	83,500	49.62	4,143,270
b	$.2146 (16) (11.5 + 4 \times .77066) 2\pi$ $= .2146 (16) (14.6064) 2\pi$	316	7.88	2490.
c	$\left(\frac{4 \times 7}{2} \right) 2\pi \left(19.5 + \frac{4}{3} \right)$ $= 28\pi (20.833)$	1,832	4.666	8550.
d	$7 \times \frac{\pi}{4} (39)^2 = 7 \times 1194.59 =$	$\frac{8,362.}{94,010}$	3.5	$\frac{29200.}{4183510.}$
C.G. $\frac{4183510}{94010} = 44.5'$				
WEIGHT = 94010. x 41 = 38,544*				

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DRAWING NO.

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

PAGE 7

By B. B. B.

2-26-62

DUG 2058

SHIPPING STRUCTURE - STEEL

ITEM

$$3 \quad \textcircled{4} \quad 24" \text{ I} = 8' \times 8\frac{1}{2} \text{ #} = 68 \text{ #}$$

$$6 \quad \frac{3}{4} \times (\frac{\pi}{4} 38.875^2 - \frac{\pi}{4} 30.875^2) = \frac{3}{4} \left(\frac{1186.9}{438.2} \right) = 328.7 \text{ in}^3 = 94 \text{ #}$$

$$2 \quad \textcircled{4} \quad 38" \quad 6 \times 6 \times \frac{3}{4} \text{ L} = 152"$$

$$\textcircled{4} \quad 50" = 200$$

$$\textcircled{4} \quad 54" = 216$$

$$\textcircled{2} \quad 68" = 136$$

$$\frac{704"}{704"} = 59 \text{ ft @ } 28.7 \text{ #/ft} = 1694 \text{ #}$$

$$\textcircled{4} \text{ Plates } 1 \times 11 \times 8\frac{1}{2} \text{ app} = \textcircled{4} \times 94 = 376 \text{ m}^3 \times .284 = 107 \text{ #}$$

$$\textcircled{4} \text{ Bolt heads \& nuts} = \textcircled{8} \times 3 \text{ hex} \times 2\frac{1}{2} = 4 \times 20 = 80 \text{ m}^3 = 23 \text{ #}$$

1986 #STRUT ASSEM

$$7 \quad \textcircled{2} \text{ BAR } \textcircled{2} \quad 9 \times 5 \times 1\frac{3}{4} = 157.5 \text{ m}^3 \times .284 = 45 \text{ #} \quad \begin{matrix} \text{H"} \\ 90.6" \end{matrix} \quad \begin{matrix} \text{M} \\ 4080 \text{ #} \end{matrix}$$

$$4 \quad \textcircled{2} \text{ PLATE } \textcircled{2} \quad 11 \times 12 \times 1\frac{1}{4} = 330 \text{ in}^3 \times .284 = 94 \quad \begin{matrix} \text{H"} \\ 84.6 \end{matrix} \quad \begin{matrix} \text{M} \\ 7950 \end{matrix}$$

$$\textcircled{4} \text{ STRUTS } 8 \times 8 \times \frac{3}{4} \text{ L } \textcircled{4} \quad \frac{(109 - 13.5 - 6.5)}{12} \times \frac{89}{3}$$

$$= 30 \text{ FT @ } 38.9 \text{ #/ft} = 1167 \quad \begin{matrix} \text{H"} \\ 46 \end{matrix} \quad \begin{matrix} \text{M} \\ 59600 \end{matrix}$$

$$5 \quad \textcircled{8} \text{ LOWER PLATES } \textcircled{8} \quad (4.5 \times 8 + 6 \times 7) + 1 = 78 \times 8$$

$$36 + 42$$

$$= 624 \text{ m}^3 \times .284 = 177 \quad \begin{matrix} \text{H"} \\ 8 \end{matrix} \quad \begin{matrix} \text{M} \\ 1416 \end{matrix}$$

$$\frac{1483 \text{ #}}{1483 \text{ #}} \quad \frac{67046}{67046}$$

TOTAL 3469 #
 net 3500 #

BASKET (PIQUA)

$$64\frac{1}{2} \times \frac{\pi}{4} 30^2 = 64.5 \times 706.86 = 45,592 \text{ m}^3$$

$$- 19 \times 64\frac{1}{2} \times \frac{\pi}{4} (5.780)^2 =$$

$$19 \times 64.5 \times 21.895 = -26,832$$

$$\frac{18,760 \text{ m}^3}{.097} = 356 \text{ AL}$$

$$- \text{CORNERS } \frac{1820 \text{ #}}{10}$$

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

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 8

10/10/2000 2-25-52

SIDE VIEW

END VIEW

$$\begin{aligned} L_c/b &= 2.9055 & L_{c/26} &= 1.45275 \\ h/b &= 2.5892 & h/c &= 1.9638 \end{aligned}$$

$$\begin{aligned} L_c/h &= 1.12217 \\ b/h &= .38621 \end{aligned}$$

$$\begin{aligned} L_b/h &= 1.07198 & L_{c/L_A} &= 1.06506 \\ L_a/b &= 2.7756 \end{aligned}$$

$$\begin{aligned} L_a/h &= 1.0536 \\ q/h &= .33183 & h &= \frac{a}{.33183} \end{aligned}$$

$$8 \times 8 \times 3/4 \text{ L} \quad 38.2 \text{ #/FT} = W$$

$$11.44 = A$$

$$69.7 = I_x > I_y$$

$$28.2 = I_z$$

$$2.47 = r_x \text{ \& } r_y$$

$$1.57 = r_z$$

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

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

STRUT LOAD

$$\begin{aligned} &= \frac{L_c}{2} = .53253 L_a \\ &= .53253 (1.0536 h) \\ &= .56107 h \end{aligned}$$

GEOMETRY AND
MEMBER STRESS RATIOS

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 9

OK'D By/And 2-26-62

FORE AND AFT LOADS

1000# PILOT LOAD APPLIED AT PLANE B AT BOTTOM OF CASK.

$$\frac{L_a}{F_H} = \frac{1874.19}{2180.548} = .8595$$

$$\text{STRUT LOAD} = \frac{L_a}{2} \times 1.06506 = .53253 L_a$$

$$\frac{a}{h} = .33183$$

$$a = F_{H2} = F_{H1} = .33183 (1778.84) = 590.274 \#$$

$$2a = 1180.548 \#$$

$$F_{V1} = -F_{V2} = \frac{92.5}{52} \times 1000 \# = \pm 1778.84 \#$$

$$L_a = 1.0536 h = 1.0536 F_V = 1874.19 \#$$

$$1 \text{ STRUT LOAD} = .53253 L_a = 998.062 \#$$

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

$$F_{H2} = F_{H3}$$

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

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

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

CO-LATERAL LOADS ON STRUTS

REFERENCE:

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DRAWING NO.

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

PAGE 10

HQ Bldg. 2-26-62

CASE 1 VERTICAL LOADING 2G DYNAMIC $\updownarrow$ + 1G STATIC $\downarrow$

MAX = 3G $\downarrow$

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

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

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

$$W_{\text{UPPER ENDS OF STRUTS}} = \frac{726^*}{60474^*}$$

$$La = 1.0536h$$

$$= 1.0536 (90711) = 95,575$$

$$1 \text{ STRUT LOAD} = .56107 h = .56107 (90711) = -50,895^*$$

$$a \text{ for 2 STRUTS} = .33183 h = .33183 (90711) = 30,100^*$$

CASE 2 FORE AND AFT LOADINGS

$$10G \text{ DYNAMIC } \leftrightarrow = 597,480^* + 7260^* \\ + 1G \text{ STATIC } \downarrow = 60,474^*$$

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

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

$$\text{PLANE B} \rightarrow .4323(597,480) = \underline{\underline{258,291}}$$

FROM VERTICAL LOADINGS

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

$$1 \text{ STRUT LOAD} = -.56107 (30237) = -16,965^*$$

$$a (2 \text{ STRUTS}) = .33183 (30237) = \underline{\underline{10,033^*}}$$

FROM HOR. LOADING - A PLANE

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

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

$$h = .81577 (346,449) = \underline{\underline{282,622^*}}$$

TOTALS

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

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

$$\text{MAX } h = 30237 + 282,622 = \underline{\underline{312,859}}$$

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

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 11

HABAD/mw

2-26-62

CASE 3 LATERAL LOADINGS

SAME AS CASE 2

604,740* LATERAL ⊙
60,474* VERTICAL ↓

$$\begin{aligned} \text{1 STRUT LOADING} &= -16,965^* \\ a(2 \text{ STRUTS}) &= 10,033^* \\ h &= 30,237^* \end{aligned}$$

$$\begin{aligned} \frac{L_c}{2a} &= 1.45275 \\ L_c &= 1.45275(173,775) \\ &= 251,653^* \end{aligned}$$

$$\begin{aligned} \text{COMBINED MAX - 1 STRUT} &= -16,965 - 251,653 \\ &= -268,618 \end{aligned}$$

$$\begin{aligned} \text{MAX. SHEAR ON TOP BOLTS} \\ &= \sqrt{173,775^2 + 30,237^2} = 175,700 \end{aligned}$$

SUMMARY

	<u>CASE 1</u>	<u>CASE 2</u>	<u>CASE 3</u>
<u>MAX. LOAD ON 1 STRUT</u> ($\frac{L_c}{2}$)	-50,895	-175,539	-268,618.
<u>MAX A-FRAME LOAD</u> (L_a)	95,575	329,630	—
<u>MAX. SHEAR TOP BOLTS</u> (h) <u>IN A PLANE</u>	90711	312,859	175,700
<u>TOTAL SHEAR AT BOTTOM</u> <u>IN B PLANE</u>	—	417,172	258,291

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STRESS ANALYSIS

DRAWING NO.

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

PAGE 12

HABackus 2-26-62

UPPER STRUT END

g - 4 SOCKET HD. SCREWS $1\frac{1}{4}-7-4\frac{1}{4}$ L6.
 STRESS AREA = .9524 in^2 thru thread
 SHEAR Y.P = 95,000 PSI
 SINGLE SHEAR = 90,200 # EACH.
 TOTAL SHEAR = $4 \times 90,200 = 360,800$ #
 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 between
 b and c
 additional weld at e and f

f = $\frac{3}{4}$ " penetration weld

e = 1" fillet weld

Total weld around block b is

$$(8+5+5) \times \frac{3}{4} = 13.5 \text{ in}^2$$

$$(8 \times 1 \times .707) = \frac{5.65}{19.15 \text{ in}^2} \times 13,600 = 260,000 \text{ #}$$

WELD BETWEEN STRUTS AND a

23" 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 = $23 + 11 = 34$ " of $\frac{3}{4}$ penetration weld all around.

$$\text{Stress} = \frac{268,618}{34 \times \frac{3}{4}} = 10,500 \text{ PSI} \quad \text{OK} \quad 13,600 \text{ allowed}$$

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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 FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 13

899 Backmo 2-26-62

UPPER END
"A" STRUT ASSEM.

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 15

of a Backus 2-26-62

LOWER STRUT END

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.

$$C = 3.22"$$

$$r_z = 1.57$$

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

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

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

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

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

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

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

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

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

$$P_{allowable} = 24450 \times 11.44 = 279,700 \#$$

$$\sec [156.36 \times .00493]$$

$$= \sec [.77085 \text{ radians}]$$

$$= \sec 44.15^\circ$$

$$= 1.3937$$

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

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 16

1049 Bock/m

2-26-62

LOWER STRUT END

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

3/4 fillet welds

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

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

3 7/8 x 2 7/8 dia.
taps on bolt and screw.
mean dia = 3 1/4"

Tension area in 2 end plates 1" T-1

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

$$S_T = \frac{268,618}{5.5} = 49,000 \text{ psi OK (100,000 y.p.)}$$

Bearing in strut ends

$$S_B = \frac{268,618}{2 \times 3 \frac{1}{4}} = 41,500 \text{ psi OK (100,000 y.p.) T-1 stock}$$

Socket Bolt. Screw - 2 1/4 dia.

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

$$= \frac{268,618}{2 \frac{1}{4} \times 1} = 119,000 \text{ psi OK (1.5 x 100,000 y.p. allow)}$$

$$S_B \text{ - bearing on bolt.} = 119,000 \text{ psi OK (1.5 x 135,000 y.p. allow)}$$

$$\text{Double Shear Strength} = 2 \times 382,000^{\#} = 764,000^{\#} \text{ OK}$$

PLATE IN BASE WELDMENT T-1 1" thick

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

$$S_S = \frac{268,618}{42.5 \times \frac{3}{4} \times .707} = 11,900 \text{ psi OK}$$

REFERENCE:

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DRAWING NO.

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FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 17

HQ Barlow 2-26-62

BOTTOM SHEAR RINGS

(on Cask and on Weldment)

$$\text{Max. Hor. Shear Load} = 417,172 \text{ \#}$$

F-2055-10

ON CASK

$$3/4 \text{ thick} \times 1\frac{1}{2} \text{ wide} \times 39 \text{ I.D.}$$

$$\text{Inner weld } \pi 42 = 132"$$

$$\text{Outer weld } \pi 39 = 122.5"$$

$$\left. \begin{array}{l} \text{Inner weld } \pi 42 = 132" \\ \text{Outer weld } \pi 39 = 122.5" \end{array} \right\} 254.5" \text{ total}$$

Due to narrow section, all of this weld length cannot be effective. Hoop stress limits shear load from weld in side opposite to direction of application of load from cask.

section

$$2 \times 3/4 \times 1\frac{1}{2} = 2.25 \text{ m}^2$$

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

$$\text{Load capacity} = 2.25 \times 30,000 = 67,500 \text{ \#}$$

of half ring transmitted by section area.

This leaves $417,172 - 67,500 = 349,672 \text{ \#}$ to be taken by welds in half perimeter.

assumed variation in intensity over a half circle is similar to that among the balls of a ball bearing.

$$\text{Max. stress} = \frac{349,672}{254.5/2} \times \left(\frac{5}{\pi}\right)$$

$$= \frac{349,672}{254.5} \times \frac{10}{\pi} = 4360 \text{ psi} \quad \text{OK } 13,600 \text{ allow}$$

RING ON WELDMENT

$$\text{Section area } 2 \times 4 \times 3/4 = 6 \text{ m}^2 \quad @ 30,000 \text{ psi Y.P.} = 180,000 \text{ \#}$$

$$\therefore \text{Weld required to take (over half circle)} = \frac{417,172}{180,000}$$

$$\text{Half perimeter weld} = 2 \times 28" = 56" \text{ of } 1/2" \text{ fillet weld}$$

$$S_s = \frac{237,172}{56 \times 1/2 \times 707} = 12,000 \text{ psi} \quad \text{OK } 13,600 \text{ psi OK}$$

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 18

OKA. Backus 2-28-62

<u>POSITION</u>	<u>D"</u>	<u>L"</u>	<u>LOAD P</u>
1	0	51.6	0
2	6.2	54.6	6775*
3	9	55.5	9685*

SHOWING PROCEDURE FOR USING
5 TON HOIST FOR RIGHTING CASK
WHEN SUSPEND ON SINGLE LUG.

CLOSURE HEAD BOLTS

must withstand load = 60 x wt head and contents of cask.
60 x 12,904 = 770,424* on 24 bolts.

$$\frac{770,424*}{24} = 32,100* \text{ each bolt}$$

use 3/4-10 Socket Hd screws OK 49,000* @ 4P

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 20

H. A. Barkus

2-26-62

CLOSURE HEAD
LIFTING LUGS & GUIDES

Required by spec. to lift 6x wt. of head plus contents of cask.

$$\text{Head} = 6344$$

$$\text{Contents} = 6560$$

$$12,904 \times 6 = 77,424 \text{ \#}$$

assume only 2 of 4 lugs are in use.

$$\text{Each lug loaded to } \frac{77,424}{2} = 38,712 \text{ \#}$$

DIRECT LIFT - load line 'G'

2 Socket & Cap Screws - $\frac{3}{4}$ " to indirect tension @ 49,000# each.

$$\text{OK } 98,000 \text{ \#} > 38,712 \text{ \#}$$

FOR INCLINED LOAD LINES E & F,

the vertical component will be the same as above for G.
The horizontal component will be resisted by 2 screws at side

$$M_r = 2 \times 49,000 \times 17\frac{1}{4} = 171,500 \text{ \#} \text{ resisting moment.}$$

$$\text{Max. allow. Hor. Component} = \frac{171,500}{5.75 \text{ \#}} = 29,800 \text{ \#}$$

$$\frac{29,800}{49,000} = .608 = \tan 31.3^\circ$$

this is OK. for load line E at 30°

For load line F at 45° , some further assistance is provided by the vertical bolts. Further support, as at line K, can give a buttressing effect to reinforce low angle sling hoists.

The Closure Head lugs do not permit lifting 6x weight of the entire loaded cask, and so are to be removed during transportation.

WELD required on each side of $1\frac{1}{2}$ " lug plate = $11\frac{1}{2}$ linear inches

$$\text{To support } \frac{38,712 \text{ \#}}{2} = 19,356 \text{ \#}$$

$$\frac{19,356}{11.5} = 1680 \text{ \#/inch required for shear only}$$

$$\text{use } \frac{1}{2} \text{ penetration weld, rated at } \frac{13600}{2} = 6800 \text{ \#/inch}$$

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 21

DTM/Boh/Kno 2-26-62

CASK LIFTING LUGS

POSITION 1

2 lugs - 60° sling

LUGS are T-1 steel
100,000 psi.

$$F_q = \frac{63248}{2 \times .866} = 36500^*$$

$$F_{01 \text{ LG}} = 63,248^*$$

$$M = .67 F_q \times 5\frac{3}{8} = .67 (36500) (5.375) = 131,200 \text{ in}^*$$

$$Z = \frac{bh^2}{6} = \frac{(2 \times 1\frac{1}{2}) (5\frac{3}{4})^2}{6} = 16.52 \text{ in}^3$$

$$S_b = \frac{M}{Z} = \frac{131,200}{16.52} = 7960 \text{ psi}$$

$$\text{Tension} = \frac{P}{A} + \frac{P \times 1.25}{(2 \times 1\frac{1}{2}) (5.5)^2 / 6}$$

$$P = 15F \\ = .75 (36500) \\ = 27,375^*$$

$$S_T = \frac{27375}{2 \times 1\frac{1}{2} \times 5.5} + \frac{1.25 (27375)}{3 \times 30.25 / 6}$$

$$= (.0827) (27375)$$

$$1660 + 2260 = 3920 \text{ psi}$$

$$\text{Combined } S_b + S_T =$$

$$7960 + 3920 = 11,880 \text{ psi}$$

$$\text{For } 6\text{ LG}, S_{\text{comb}} = 6 \times 11,880 = 71,280 \text{ psi OK (100,000 psi.)}$$

2 lugs - 45° sling

$$F_q = \frac{63248}{2 \times .707} = 44,729^*$$

$$M = .83 F_q \times 5\frac{3}{8} = .83 (44729) (5.375) = 199,500 \text{ in}^*$$

$$S_b = \frac{199,500}{16.52} = 12,100 \text{ psi}$$

$$P_b = .55 F_q = .55 (44729) = 24600^*$$

$$S_T = \frac{P}{A} + \frac{P \times 1.25}{3 \times (5.5)^2 / 6} = \frac{24600}{3 \times 5.5} + .0827 (24600) \\ = 1490 + 2040 = 3530.$$

$$\text{Combined } S_b + S_T = 12100 + 3530 = 15,630$$

$$\text{For } 6\text{ LG } S_{\text{comb.}} = 6 \times 15630 = 93780 \text{ psi OK (100,000 psi.)}$$

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DRAWING NO.

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PAGE 22

OK'd by [signature] 2-26-62

POSITION 2

$$GG = 6 \times 63248 \text{ (including shipping structure)} \\ = 379,488 \# \text{ on one leg}$$

$$ST = \frac{379,488}{3 \times 5.5} + 379,488 (0.827) = 23,000 + 31,400 = 54,400 \text{ psi}$$

BRACKET BOLTS assume GG load in direction C. screws in shear.

use 8 socket head screws $\frac{7}{8}$ " - 9 single shear area = 4.578 in^2
 single shear for 8 screws = $8 \times 4.578 \times 105,000 \text{ S.P.} = 380,000 \#$
 OK

assume GG in direction D.

Tension on bolts $\frac{379,488}{8} = 47,436 \# \text{ each}$ OK
 (67,700 # S.P.)

BRACKET T-1 stock, 100,000 psi S.P.

load in direction D

area in tension 2 brackets $\times$ 2" width $\times$ 2 $\times$ $\frac{7}{8}$ " section = 7 in^2

$$ST = \frac{379,488}{7 \text{ in}^2} = 54,213 \text{ psi} \quad (\text{OK } 100,000 \text{ S.P.})$$

Bending in section $1\frac{3}{4}$ " from C

$$M = \frac{379,488}{4} \times 1\frac{3}{4} = 166,026 \text{ in} \cdot \#$$

$$Z = \frac{(2 \times 2) \times 2^2}{6} = \frac{16}{6}$$

$$S_b = \frac{M}{Z} = \frac{166,026}{\frac{16}{6}} \times \frac{3}{8} = 62,260 \text{ psi}$$

shear through section at inner bolts.

$$\text{Net area} = (2 - \frac{7}{8}) 2 = 2.25 \text{ in}^2$$

$$S_s = \frac{379,488}{4 \times 2.25} = 42,160 \text{ psi}$$

BRACKET PIN $1\frac{3}{4}$ " - 5 Socket Head Screw

$$\text{Double Shear} = 231,000 \times 2 = 462,000 \#$$

Bearing $S_c = \frac{379,488}{1\frac{3}{4} \times 2 \times 1\frac{1}{2}} = 72,500 \text{ psi}$ OK T-1 stock
 (100,000 S.P.)

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DRAWING NO.

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PAGE 23

OFA/BAD/HWO 2-26-62

PHILOSOPHY OF DESIGN

SHIPPING STRUCTURE

1. 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 stressed 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.

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PAGE 24

of Rods 2-76 62

2. 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 inclined, ball ended "clothespoles" as 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 structure.

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DRAWING NO.

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PAGE 23

HAB/pus 2-76-62

SIMPLE BEAM LOADING OF CASK.

Paragraph 72: 32 a requires 10G weight application when supported horizontally as a simple beam.

$$\text{Load} = 10 \times \text{WT} = 10 \times 59,745 = \underline{597,450}^{\#}$$

uniformly distributed along 92.5" beam length.

$$W = \frac{597,450}{92.5} = 6459^{\#/\text{in}}$$

$$\text{Max. moment as a beam} = \frac{WL^2}{8}$$

$$\text{Max. deflection} = \frac{5}{384} \frac{WL^3}{EI}$$

assume only outer shell is effective.

$$\begin{aligned} \text{O.D.} &= 49" & \text{I.D.} &= 47" & I &= .0491 (49^4 - 47^4) \\ & & & & &= .0491 (2401^2 - 2209^2) \\ & & & & &= .0491 (5,764,801 - 4,879,681) \\ & & & & &= .0491 (885,120) = 43,459.392 \\ Z &= \frac{43,459.392}{92.5} = \underline{1,773.8} \end{aligned}$$

$$M = \frac{597,450 \times 92.5}{8} = 6,908,362.5$$

$$S_b = \frac{M}{Z} = \frac{6,908,362.5}{1,773.8} = 3894.6 \text{ psi}$$

$$\text{max. defl.} = \frac{5}{384} \frac{597,450}{30 \times 10^6} \frac{(92.5)^3}{43,459} = \underline{.004,725}^{\prime\prime}$$

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PAGE 26

WABachman 2-26-62

STRUCTURAL INTEGRITY UNDER IMPACT.

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 would 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.

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WILMINGTON, DEL.

PAGE 27

At a Bafun

2-26-62

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 $120,000^{\#}$ cask 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 60G load, (or waivers for $1\frac{1}{8}$ " steel thickness) and par. 72:34, covering 6" punctured areas, uses a 30G load, or waivers for $\frac{7}{8}$ " steel thickness.

The energy absorbed by the cask from such loadings can be expressed as K.E. in foot-lbs. Since this will be converted into strain energy of the cask 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

$$P.E. = W \times 15 \text{ ft} \quad \text{ft. lbs.}$$

$$\text{Impulse} = 60 W \times .016 \quad \text{pound seconds}$$

$$= MV$$

$$\therefore V = \frac{60 W \times .016}{M} = .016 \times 60 \times 32.16 = 30.87 \text{ ft/sec}$$

$$K.E. = \frac{MV^2}{2} = \frac{W}{32.16} \frac{(30.87)^2}{2} = 14.82 W \quad \text{ft lbs.}$$

For Par 72:34

$$\text{Impulse} = 30 W \times .016 \quad \text{pound seconds.}$$

$$V = 30 \times .016 \times 32.16 = 15.435 \text{ ft/sec.}$$

$$K.E. = \frac{MV^2}{2} = \frac{W}{32.16} \frac{(15.435)^2}{2} = 3.705 W \quad \text{ft lbs}$$

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.

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DRAWING NO.

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PAGE 28

GA Backus 2-26-62

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.

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

Plastic Energy

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

$$U = 30,000 \text{ }^{\#} \times .30 \text{ }^{\#} = \underline{\underline{9000}} \text{ in}^2/\text{cu in}$$

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.

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STRESS ANALYSIS

DRAWING NO.

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FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 29

Of 9 Backus 2-26-62

Again, in reference, using 4500 [#]/cu in as max KE value
Par 72:32 $KE = W \times 15 \times 12 = 60,000 \times 180 = 10,800,000$ [#] ⁱⁿ

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

Par 72:34 $KE = \frac{1}{4} \times 10,800,000 = 2,700,000$ [#] 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 $\pi/2$.

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.

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PAGE 30

By A. Backus 2-26-62

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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DRAWING NO.

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PAGE 31

of 9 Back 2-26-62

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

$t_s = .75$ " for clad shell

$$p' = \frac{E(\frac{t}{R})}{1 + \frac{1}{2}(\frac{\pi R}{m l})^2} \left\{ \frac{1}{m^2 \left[1 + \left(\frac{m l}{\pi R} \right)^2 \right]^2} + \frac{R^2 t^2}{12 R^2 (1 - \nu^2)} \left[1 + \left(\frac{\pi R}{m l} \right)^2 \right]^2 \right\}$$

where m = no. lobes formed in buckling

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

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

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

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

$$\text{for } m=10 \quad p' = \frac{1.44 \times 10^6}{1.132} \left\{ \frac{1}{2300} + 214 \times 10^{-4} (.66) \right\} = 1.27 \times 10^6 \times .0247 = \underline{31,300 \text{ psi}}$$

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STRESS ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED
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WILMINGTON, DEL.

PAGE 32

of A Backus 2-26-62

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

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

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

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

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

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

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

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

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

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

$$P' = \frac{1.44 \times 10^6}{1.27} \left\{ \frac{1}{49 (2.85)^2} + 49 \times 2.14 \times 10^{-4} (1.54)^2 \right\}$$

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

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 (t) on (P') .
again, for $m=6$ let t be reduced to $\frac{3}{8}$ ", or half the original value.

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

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

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

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

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

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

$$P' = \frac{720,000}{1.0325} \left\{ \frac{1}{400 (16.5)^2} + 400 \times 2.14 \times 10^{-4} [1.065]^2 \right\}$$

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

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PAGE 33

Q9 Backus 2-26-62

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 lead to about 1180 psi for commercial lead).

The approximate pressure required to collapse the cylindrical configuration would be

For $m = 10$

$$\begin{aligned} P' &= \frac{30 \times 10^6 \frac{1}{2}}{1 + \frac{13.2}{10^2}} \left\{ \frac{1}{10^2 \left[1 + \frac{10^2}{26.4} \right]^2} + \frac{10^2 \times (1/2)^2}{12 \times 15.5^2 (91)} \left[1 + \frac{26.4}{10^2} \right]^2 \right\} \\ &= \frac{968,000}{1.132} \left\{ \frac{1}{100 (4.8)^2} + 0.00955 [1.264]^2 \right\} = 852,000 \left\{ \frac{1}{2300} + 0.0152 \right\} \\ &= 852,000 (0.0156) = \underline{13,300 \text{ psi}} \end{aligned}$$

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.

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STRESS ANALYSIS

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FOOT OF WEST ST.

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PAGE 34

10900000 2-26-62

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

Energy required to compress cylindrical ring radially inward is approximately $U = 142,500 \text{ lb} \times 2.09 \text{ in} = 300,000 \text{ in-lb}$, 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 cock.

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PAGE 35

W.A. Backus 2-26-62

IMPACT OF CASK ON ITS BOTTOM SURFACE

Distribution of 60W loads

$$\begin{aligned}
 \text{Head } 60 \times 6344 &= 380,640 \text{ lbs total} \\
 \text{Cask } 60 \times 8300 &= 498,000 \text{ lbs steel} \\
 60 \times 38,544 &= 2,312,640 \text{ lbs lead} \\
 \text{Bottom } 60 \times 6560 &= 393,600 \text{ lbs} \\
 \hline
 &= 3,584,880 \text{ lbs}
 \end{aligned}$$

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

$$\begin{aligned}
 &\frac{380,640 + 393,600 + 498,000}{1,272,240 \text{ lbs}} \\
 &\frac{1,272,240}{\pi(49^2 - 46.5^2)} = \frac{1,272,240}{\frac{1885 - 1698}{187 \text{ in}^2}} = \underline{6810 \text{ psi compressive}}
 \end{aligned}$$

Pressure of lead on bottom plate at level A

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

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

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

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

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

$$\text{Elongation of circumference} = 316.6 \times 150.8 \times 10^{-6} = .047700 \text{"}$$

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

$$\text{KE} = 874,000 \times .0477 = \underline{41,700 \text{ in} \cdot \text{lbs}} \text{ at } 19,000 \text{ psi hoop stress}$$

Just above the knuckle (8" up)

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

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

app 25010 psi approx elastic.

REFERENCE:

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DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 36

FOOT OF WEST ST.

WILMINGTON, DEL.

BAKERS 2-26-62

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 $3\frac{1}{2}$ M force and 2.7 M 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.

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

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

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

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

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

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

REFERENCE:

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DRAWING NO.

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FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 37

DATA BACKUS 2-26-62

Second, note that the steel shell will yield, as much as is required to relieve the pressure from the lead, when the hoop stress has exceeded 30,000 psi. The rate of stretch will not be inconsistent with the pressure, which varies over a 92" hydraulic "lead", whenever that exceeds 30,000 psi. That is, at the bottom, where the hydrostatic pressure from dynamic and static forces, is greatest, the tensile stress of the steel will also be the greatest, as grossly indicated by the rising portion of the stress-strain curve of the material.

This tends to keep the stretch of the cylinder more nearly uniform, below the level at which 30,000 psi is developed.

The solution, then, is to find enough volume of steel to stretch
 a) below the 30,000 psi hydrostatic stress level and
 b) without the max. pressure at level A exceeding a "safe" sub-ultimate stress.

assumed 40,000 max hoop stress

average hoop stress over lower 23" of cast shell wall = 35,000 psi

$$\text{Hoop force} = 35,000 \text{ psi} \times 23' \times 1" = 805,000 \#$$

$$\text{mean circumference} = 150.8"$$

stretch required to develop 2,700,000 in-lb is

$$\frac{2,700,000 \text{ in-lb}}{805,000 \#} = 3.36" \quad (\approx 1.07" \text{ dia. increase})$$

$$\text{This is } \frac{3.36}{150.8} = 2.23\% \text{ elongation} \quad \text{Very reasonable.}$$

The radial pressure required to develop 40,000 psi hoop stress is

$$Q = \frac{2St}{r} = \frac{2 \times 40,000 \times 1"}{47} = 1700 \text{ psi}$$

The axial pressure required is

$$P = \frac{Q}{.755} = \frac{1700}{.755} = 2250 \text{ psi} \quad \text{— for lead max}$$

By previous calculations, 1365 psi resulted from 60 G loading

Therefore, in free fall, G loading would go up to $\frac{2250}{1365} \times 60 = 100 \text{ G}$
 to be consistent with assumption above.

The cast design, would, however, be safe under both methods of analysis.

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PAGE 38

At a Barbus 2-26-62

IMPACT OF CASK ON ITS TOP SURFACE

Due to curvature of top surface, initial flattening within the plastic range will occur. This will slightly increase curvature at d and result in an assumed area, approx. 30" in diameter over which the external load may be considered as acting as a piston.

Condition 1.

The hydrostatic pressure corresponding to this ram force is

$$p = \frac{3,584,880}{\pi \times 30^2} = \frac{3,584,880}{706} = 5080 \text{ psi}$$

area a, receives this pressure directly, and load F is therefore total load on a.

Shear at perimeter of area a is, for 1 1/4 thickness

$$S_s = \frac{3,584,880}{\pi \times 30 \times 1 \frac{1}{4}} = 29,700 \text{ psi}$$

For 1 3/8 thickness

$$S_s = \frac{3,584,880}{\pi \times 30 \times 1 \frac{3}{8}} = 27,000 \text{ psi}$$

OK, Shear ult = 36,000 psi min.

Under this condition, area b is transmitting the load F to the cask, assisted by some smaller force transmitted directly thru the dished head itself.

The head, operating under the internal pressure $p = 5080 \text{ psi}$ has a hoop stress at the juncture (e) of $\frac{5080 \times 24}{1} R = 122,000 \text{ psi}$

This is not allowable, and must be limited to about half this value.

Condition 2 This must transmit at least half of load F directly to area b.

The ultimate allowable unit stress - for arcwelding on carbon steel without heat treatment, is 51,000 psi. To transmit $\frac{3,584,880}{2}$ lbs would require $\frac{3,584,880}{2 \times 51,000} = 35 \text{ in}^2$ min. weld area

This is conveniently supplied by 6 $\frac{1}{2}$ 6x6x3/4 with total area = $6 \times 8.44 = 50.64 \text{ in}^2$

load capacity at 51,000 psi for weld and angle is

$$P = 50.64 \times 51,000 = 2,580,000 \text{ lbs, leaving}$$

$$\frac{3,584,880 - 2,580,000}{\pi \times 30^2} = \frac{1,004,880}{706} = 1415 \text{ psi as hydrostatic pressure.}$$

REFERENCE:

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DRAWING NO.

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FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 39

HQ Backus 2-26-62

Condition 3 Due to the void space in the head, the hydrostatic pressure indicated would not be developed until after collapse of the $\angle$ s. Therefore increase the area of the angles to take the whole load.
Use 6 angles $8 \times 8 \times 3/4$ with total area = $6 \times 11.44 = 68.64 \text{ in}^2$

$$S_c = \frac{3,584,880}{68.64} = 52,220 \text{ psi} \quad \text{OK.}$$

This is substantially the whole load within the capacity of the angles alone. No account is taken of the load carried directly by the dished head.

This condition is considered safe against rupture in the head, and transmits the impact energy into the cask itself, where substantially the same expansion phenomenon will take place at the outer wall as was calculated for the cask when impact was made on its bottom surface.

IMPACT AGAINST EDGE OF HEAD.

Spec 72.32(c) requires the lid (or head) to sustain $15 \times \text{rot. loaded cask}$ at any point.

$F = 15 \times 59,748 = 896,220^{\#}$ This is taken directly by a lip
whose projected area is $5/8 \times 49 = 30.6 \text{ in}^2$
Bearing stress is $\frac{896,220}{30.6} = 29,400 \text{ psi} \quad \text{OK} \quad 30,000 \text{ psi}$

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DRAWING NO.

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PAGE 40

HQ Backus 2-26-62

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 outboard 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
$(3.5 \times 2) = 7.0$	$7.0 \times 1 = 7.0$	
$(2.5 \times 2.5) = 6.25$	$6.25 \times 1.25 = 7.82$	
$(10.5 \times 1/8) = 11.82$	$11.82 \times 7.25 = 85.7$	
$(8.5 \times 1/8) = 9.56$	$9.56 \times 6.75 = 64.5$	
$Y = 4.75$	34.63	165.02

$$\frac{R}{C} = \frac{21.25}{7.75} = 2.75$$

$$I = \frac{6.0 \times 4.75^3}{3} - \frac{2.38 \times 2.75^3}{3} - \frac{1.38 \times 2.25^3}{3} + \frac{1/8 \times 7.75^3}{3} + \frac{1/8 \times 6.25^3}{3}$$

$$= 214.2 - 16.45 - 5.23 + 175.4 + 96.5 = 459.$$

$$C = 7.75 \quad \text{for } R/C = 2.75 \quad K = \text{app } 1.4 \text{ in } S = K \frac{MC}{I} \quad (\text{Sally})$$

Roark VIII-1

$$M = .3183 WR = .3183 \left(\frac{60}{2} \times 59,748 \right) 21.25 = 12,100,000 \text{ " #}$$

$$SB = \frac{12,100,000 \times 1.4 \times 7.75}{459} = 286,000 \text{ psi. for 30G without assist. and with 2 point loading.}$$

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.

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PAGE 41

KAB:apw 2-26-62

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

$$S = \pi(1.81a) \left[1 + \frac{1}{4} \left(\frac{.19a}{1.81a} \right)^2 + \frac{1}{64} (.104972)^6 + \frac{1}{256} (.104972)^6 \dots \right]$$

$$= 5.68628876a$$

$$= 5.7019252a$$

1.00	2.75478
.00	0.00190
.000	.00000
1.002	2.75668

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 (axial)

$$Q = (30,000 \text{ psi} \times 1 \times 1) \times 1.2546 = 37,638 \text{ in-lbs per inch length shell}$$

For 92" of load length of shell, total energy of this expansion is

$$92 \times 37,638 = 3,460,000 \text{ in-lbs}$$

$$\text{Required energy} = 10,800,000 \text{ " for spec 72.32}$$

Note that the above 3,460,000 in-lbs represents an expansion of only .832%
Proportionately, full 10,800,000 in-lbs would be absorbed by 2.6% expansion

Addendum To Page 38

To accomplish 10,800,000 in-lbs energy absorption for bottom impact

assume hoop stress 50,000 psi max. mean value 40,000 psi.

$$\text{Hoop force} = 36.8 \times 1" \times 40,000 = 1,472,000 \text{ \#}$$

$$\text{Reqd stretch} = \frac{10,800,000}{1,472,000} = 7.32" (= 2.33" \text{ dia exp})$$

$$\text{Radial pressure} = \frac{2 \times 50,000 \times 1}{47} = 2125 \text{ psi} \quad \text{Cylind press} = \frac{2125}{.755} = 2820 \text{ psi}$$

No rupture will result.

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PAGE 42

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ESTIMATED DISTORTION OF CYLINDER
DUE TO IMPACT ON PLANE SURFACE.

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PAGE 43

APPROVED 2-26-62

ANALYSIS OF VARIOUS PROPORTIONS

FOR INNER VESSEL.

$d = 30''$ SECTION AT t_s EFFECTIVE FOR LENGTH $5\frac{1}{2}''$

Coefficients are taken from ASME tables for cylindrical vessels with flat plate closures, as given in "Process Equipment Design", Brownell & Young, pg 108.

CASE	t_h	t_s	$\frac{t_h}{t_s}$	d/t_h	d/t_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	$1\frac{1}{4}$	$\frac{3}{4}$	$\frac{5}{3}$	24	40	-50.5	+1.4	+1.58	+30.5	-.6355	-.95
D	$1\frac{1}{2}$	$\frac{3}{4}$	2	20	40	-42.	+1.4	+1.31	+25.4	-.6355	-.79

General formulae

$$\beta = \sqrt[4]{\frac{12(1-\mu^2)}{d^2 t_s^2}}$$

$$= \sqrt[4]{\frac{12(.91)}{30^2 t_s^2}}$$

$$\beta^2 = \frac{.11}{t_s}$$

$$\beta = \sqrt{\frac{.332}{t_s}}$$

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 $t_s =$

$$f_a = \frac{pd}{4t_s} = \frac{100 \text{ psi} \times 30''}{4t_s} = \frac{750}{t_s}$$

$$M_0 = pd^2 \left[\frac{(a_3 - a_6)(b_5 - b_2) - (a_5 - a_2)b_3}{(a_4 - a_1)(b_5 - b_2) - (a_5 - a_2)(b_4 - b_1)} \right]$$

$$pd^2 = 90,000.$$

$$Q_0 = pd \left[\frac{(a_4 - a_1)b_3 - (a_3 - a_6)(b_4 - b_1)}{(a_4 - a_1)(b_5 - b_2) - (a_5 - a_2)(b_4 - b_1)} \right]$$

$$pd = 3000.$$

Shell combined stresses

$$f_{axial \text{ combined}} = \frac{pd}{4t_s} + \left| \frac{GM_0}{t_s^2} \right|$$

$$f_{circumferential \text{ combined}} = \frac{pd}{2t_s} + \left| \frac{3d(3M_0 + Q_0)}{t_s} \right| + \left| \frac{\mu GM_0}{t_s^2} \right|$$

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DRAWING NO.

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FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 44

2-26-62

CASE	$(a_3 - a_6)$	$(b_5 - b_2)$	$(a_3 - a_6)(b_5 - b_2)$
A	$+1.97 + .425 = +2.395$	$-2.0 + .6355 = -1.3645$	-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	$+1.31 + .425 = +1.735$	$-2.0 + .6355 = -1.3645$	-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

$$M_0 = 90,000 \left[\frac{-2.37 - 10.18}{(-90.18)(-2.37) - (-12.897)(-71.38)} \right] = 90,000 \left[\frac{-12.55}{+213.5 - 918.} \right] = 1602.$$

$$Q_0 = 3,000 \left[\frac{(-90.18)(-.79) - (+1.735)(-71.38)}{-704.5} \right] = 3,000 \left[\frac{+71. + 123.5}{-704.5} \right] = -829.$$

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FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 45

QA Backus 2-26-62

SHELL COMBINED STRESSES

$$f_{axial, \text{omb}} = \frac{pd}{4t_s} + \left| \frac{6M_o}{t_s^2} \right| = \frac{750}{t_s} + \left| \frac{6M_o}{t_s^2} \right|$$

$$\text{Case A} \quad \frac{750}{1/2} + \frac{6(1530)}{(1/2)^2} = 1,500 + 36,750 = 38,250 \text{ psi}$$

$$\text{Case B} \quad \frac{750}{.75} + \frac{6(1900)}{.75^2} = 1000 + 20,250 = 21,250 \text{ psi}$$

$$\text{Case C} \quad \frac{750}{.75} + \frac{6(1670)}{.75^2} = 1000 + 17,800 = 18,800 \text{ psi}$$

$$\text{Case D} \quad \frac{750}{.75} + \frac{6(1602)}{.75^2} = 1000 + 17,100 = 18,100 \text{ psi}$$

$$f_{circumferential, \text{omb}} = \frac{pd}{2t_s} + \left| \frac{3d(3M_o + Q_o)}{t_s} \right| + \left| \frac{46M_o}{t_s^2} \right|$$

$$\begin{aligned} \text{Case A} \quad & \frac{1500}{.50} + \left| \frac{.469(30)(.469 \times 1530 + 912)}{.50} \right| + \frac{1.8 \times 1530}{.25} \\ & = 3000 + \left| 28.14(717 - 912) \right| + 11,000 = 3000 + 5500 + 11,000 = 19,500 \text{ psi} \end{aligned}$$

$$\begin{aligned} \text{Case B} \quad & \frac{1500}{.75} + \left| \frac{.383(30)[.383 \times 1900 - 904]}{.75} \right| + \frac{1.8 \times 1900}{.5625} \\ & = 2000 + \left| 15.3(728 - 904) \right| + 6095 = 2000 + 2690 + 6095 = 10,785 \text{ psi} \end{aligned}$$

$$\begin{aligned} \text{Case C} \quad & \frac{1500}{.75} + \left| \frac{.383(30)[.383 \times 1670 - 840]}{.75} \right| + \frac{1.8 \times 1670}{.5625} \\ & = 2000 + \left| 15.3[640 - 840] \right| + 5350 = 2000 + 3060 + 5350 = 10,410 \text{ psi} \end{aligned}$$

$$\begin{aligned} \text{Case D} \quad & \frac{1500}{.75} + \left| \frac{.383(30)[.383 \times 1602 - 829]}{.75} \right| + \frac{1.8 \times 1602}{.5625} \\ & = 2000 + \left| 15.3[614 - 829] \right| + 5130 = 2000 + 3290 + 5130 = 10,420 \text{ psi} \end{aligned}$$

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.

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PAGE 46

HQB/nd 2-26-62

Outer shell

$$\beta = \frac{1.28}{\sqrt{1.2}} = \frac{1.28}{\sqrt{24 \times 1}} = \frac{1.28}{4.899} = .262$$

$$\beta l = .262 \times 93 = 24.4''$$

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

$$\beta x = 2.36$$

$$x = \frac{2.36}{.262} = 9''$$

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)

$$\Delta R = \frac{S_T}{E} R = \frac{2400}{29 \times 10^6} \times 24 = .00198''$$

Bending moment M in the shell at the bottom is

$$\frac{M}{y} = \frac{K}{2\beta^2} \quad \text{where } K = \frac{ET}{R^2} = \frac{29 \times 10^6 \times 1}{24^2} = 50,400$$

$$M = \frac{yK}{2\beta^2} = \frac{.00198 \times 50,400}{2(.262)^2} = 731 \text{ in-lbs per inch width and strip}$$

$$\underline{\text{Stress}} = \frac{6M}{t^2} = \frac{6 \times 731}{1^2} = \underline{4386 \text{ psi}} \text{ tensile inside bottom shell.}$$

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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

PAGE 47

AtaBachus 2-26-62

STRESS ANALYSIS OF CLOSURE HEAD

BOTTOM PLATE, 100 psi

The head has an offset in the bottom plate and an arrangement of six angles which quite rigidly brace it from the upper formed head.

$$r_2 = 1.57$$

$$GI_{22} = 6 (17.44 \times 1.57^2) = 169.2$$

assume that the influence of the six angles is uniformly distributed around the entire inner diameter of (c), adding to the stiffness of (c). Consider a radial strip beam 1" wide.

$$\text{For (d)} \quad I_d = \frac{169.2}{2\pi/12} = \frac{169.2}{\pi \cdot 27} = 2.$$

The relative stiffness of sections (d) and (c) are

$$\text{For (d)} \quad \frac{I_d}{l_d^3} = \frac{2}{7^3} = \frac{2}{343} = .00583$$

$$\text{For (c)} \quad I_c = \frac{bt^3}{12} = \frac{1 \times (1\frac{1}{8})^3}{12} = .119$$

$$\frac{I_c}{l_c^3} = \frac{.119}{850} = .00014 \text{ which is negligible compared with (d)}$$

It is therefore justified in assuming the entire support for (c) comes from (d). Consider an "equivalent construction" (above) in which (d) is an extension of (c), resembling a cylindrical shell with a stepped diameter.

section (d) is, however, close enough to (a) to influence it very largely. It will be conservative, therefore, to assume a simplified "conservative equivalent construction" of a pressure vessel with a wall 2.88" thick, since

$$I_d = 2 = \frac{bt_d^3}{12} = \frac{t_d^3}{12}$$

$$t_d^3 = 12 \times 2 = 24 \quad t_d = 2.88"$$

The external pressure is 100 psi.

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 48

At 900 psi 3-7-62

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 $\frac{d}{t_h} = \frac{30}{1\frac{1}{8}} = 26.7$

$q_1 = -2.1 \times 26.7 = -56.$

$q_2 = +1.4$

$q_3 = +.06563 \times 26.7 = +1.71$

$b_1 = +1.27 \times 26.7 = +34.$

$b_2 = -.6355$

$b_3 = .03972 \times 26.7 = -1.06$

For the cylinder

$\frac{t_h}{t_s} = \frac{(1\frac{1}{8})}{2.88} = .39$

By interpolation based on $\frac{t_h}{t_s} = 1.0$

$\frac{d}{t_s} = \frac{30}{2.88} = 10.4$

$q_4 = -6.45$

$q_5 = -1.12$

$q_6 = -.083$

$b_4 = (.39)^2 (-5.7485) = -.875$

$b_5 = (.39)^2 (-.50) = -.076$

Substituting in

$$M_0 = pd^2 \frac{(q_3 - q_4)(b_5 - b_2) - (q_5 - q_3)b_3}{(q_4 - q_1)(b_5 - b_2) - (q_5 - q_3)(b_4 - b_1)}$$

$$= 100(30)^2 \frac{(+1.71 + .083)(-.076 + .6355) - (-1.12 - 1.4)(-1.06)}{(-6.45 + 56)(-.076 + .6355) - (-1.12 - 1.4)(-.875 - 34)}$$

$$= 90,000 \frac{(+1.793)(+.5595) - (-2.52)(-1.06)}{(+49.55)(+.5595) - (-2.52)(-34.875)}$$

$$= 90,000 \frac{+10 - 2.675}{+27.75 - 88} = 90,000 \frac{-1.675}{-60.25} = +2500$$

$$Q_0 = pd \frac{(q_4 - q_1)b_3 - (q_3 - q_6)(b_4 - b_1)}{(q_4 - q_1)(b_5 - b_2) - (q_5 - q_3)(b_4 - b_1)}$$

$$= 100(30) \frac{(-6.45 - 56)(-1.06) - (+1.71 - .083)(-.875 - 34)}{(-6.45 + 56)(-.076 + .6355) - (-1.12 - 1.4)(-.875 - 34)}$$

$$= 3000 \frac{(-52.6 + 62.45)}{60.25} = 3000 \frac{+9.85}{-60.25} = -491$$

For the flat plate

$f_{shear} = \frac{3}{2} \frac{Q_0}{t_h} = \frac{3pd}{8t_h} = \frac{3(100)30}{8(1\frac{1}{8})} = 1000 \text{ psi}$

$f_{tang.comb.} = \left| \frac{Q_0}{t_h} \right| + \left| \frac{6M_0}{t_h^2} - \frac{3Q_0}{t_h} \right| = \left| \frac{-491}{1\frac{1}{8}} \right| + \frac{6(2500)}{(1\frac{1}{8})^2} - \frac{3(-491)}{1\frac{1}{8}}$

$$= 436 + (11860 + 1310) = 436 + 13,170 = 13,606 \text{ psi max}$$

OK 30,000 psi sp.

$f_{circum.comb.} = \left| \frac{Q_0}{t_h} \right| + \left| \frac{6M_0}{t_h^2} - \frac{3Q_0}{t_h} - 6p \left(\frac{d}{t_h} \right)^2 \frac{(1-\mu)}{32} \right|$

$$= 436 + 13,170 - 6(100) \left(\frac{30}{1\frac{1}{8}} \right)^2 \frac{.20}{32}$$

$$= 13,606 - 9325 = 4281 \text{ psi}$$

The closure head is safe under 100 psi pressure.

REFERENCE:

STRESS ANALYSIS

DRAWING NO.

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PAGE 49

049 Baprus 3-7-62

FIRE TEST ANALYSIS

A CONCEPT OF A "STANDARD FIRE" AS A RADIATING SOURCE;
THE DETERMINATION OF ITS TIME-TEMPERATURE AND DERIVED DATA;
THE USE OF THESE DATA TO ESTIMATE THE FINAL ONE HOUR TEMPERATURE
OF THE PRESENT CASK DESIGN; THE EVOLUTION OF A SIMPLE FORMULA
FOR THE SAME DESIRED FINAL TEMPERATURE; AND CONSIDERATION OF
STRAINS IN THE PLASTIC CONDITION WHICH ARE REQUIRED IN PARTS OF
THE CASK TO ACCOMMODATE EXCESS EXPANSION OF THE LEAD CONTENT.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED
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PAGE 1

H. J. Backus 2-20-62

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 coeff. (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 formulae 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

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 2

FOOT OF WEST ST.

WILMINGTON, DEL.

H. D. Backus 2-20-62

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 differential through the cast. A mean cast temperature (T_x) 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:

FIRE TEST ANALYSIS

DRAWING NO.

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FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 3

OK Backus 2-20-62

EVALUATION OF (h_r) IN $[h_r A_r (T_1 - T_2)]$

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 smaller differential of temp.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS, INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 4

ATX Backus 2-20-62

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

$$= .174 (10^{-8}) \text{ Btu}^{-1} \text{ ft}^{-2} \text{ F}^{-4}$$

(or more recently .1714)

$$\therefore \phi = .174 A \left(\frac{T}{100}\right)^4$$

for black bodies only

For gray radiators

$$\phi_{g1} = E_{g1} \sigma A T^4$$

$$= E .174 A \left(\frac{T}{100}\right)^4$$

P 231

$$\therefore q_{12} = E_1 \sigma A_1 (T_1^4 - T_2^4)$$

Btu/hr

from interaction by reflection radiation.

P 238

Combined convection and radiation

Rate of heat flow from outer surface 2 to wall temp 3 is

$$q = h_c A_2 (T_2 - T_3) + E_2 \sigma A_2 (T_2^4 - T_3^4)$$

[radiation] 2 to 3

h_c = coef of heat transfer due to convection

Heat flows from surface 1 to outer surface 2 according to

$$q = \frac{K 2\pi L (T_1 - T_2)}{\ln(r_2/r_1)}$$

[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

$$\text{let } q_2 = h_2 A_2 (T_2 - T_3) \text{ where } h_2 = E_2 \sigma (T_2^2 + T_3^2)(T_2 + T_3)$$

$$\therefore q = h_c A_2 (T_2 - T_3) + h_2 A_2 (T_2 - T_3) = (h_c + h_2) A_2 (T_2 - T_3)$$

(see table VII - 1 p 239)

Per linear foot,

$$q' = \frac{q}{L} = \frac{K 2\pi (T_1 - T_2)}{\ln r_2/r_1} = (h_c + h_2) 2\pi r_2 (T_2 - T_3)$$

$$\therefore (h_c + h_2) = \frac{K (T_1 - T_2)}{r_2 (T_2 - T_3) \ln r_2/r_1}$$

REFERENCE:

REFERENCE FORMULAE - HEAT TRANSFER
FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 5

OK Backus 2-20-62

In the case of the thermocouple pipe, which is our only information source of the characteristics of our "furnace", the equation reduces to

$$q_{\text{pipe}} = \epsilon A_r \sigma (T_f^4 - T_p^4) = \epsilon A \sigma (T_f^4 - T_p^4)$$

Further, since no fins are involved here, $A_r = A_c = A$
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 $\sigma = .174 \times 10^{-8}$

$$h_2 = \frac{.1566}{100} \left[\left(\frac{T_f}{100} \right)^2 + \left(\frac{T_p}{100} \right)^2 \right] \left[\frac{T_f}{100} + \frac{T_p}{100} \right] \quad \text{or } \frac{.1566}{100} [R_2][R_1] \text{ as used below}$$

This represents a family of curves based on a choice of T_p values.

$$T_p = t_p + 460$$

$$T_f = t_f + 460$$

$$(\Delta t)_p = (t_f - t_p)$$

T_p °F	$(\Delta t)_p$	t_f °F	T_f °R	$\left(\frac{T_f}{100}\right) + \left(\frac{T_p}{100}\right) = [R_1]$	$\left(\frac{T_f}{100}\right)^2 + \left(\frac{T_p}{100}\right)^2 = [R_2]$	h_2
68	50	118	578	5.78	5.28	11.06
	100	168	628	6.28	"	11.56
	150	218	678	6.78	"	12.06
	200	268	728	7.28	"	12.56
	300	368	828	8.28	"	13.56
	400	468	928	9.28	"	14.56
	500	568	1028	10.28	"	15.56
	600	668	1128	11.28	"	16.56
	700	768	1228	12.28	"	17.56
	800	868	1328	13.28	"	18.56
	900	968	1428	14.28	"	19.56
	1000	1068	1528	15.28	"	20.56
	1100	1168	1628	16.28	"	21.56
	1200	1268	1728	17.28	"	22.56

Table T₁

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 6

FOOT OF WEST ST.

WILMINGTON, DEL.

At a Backus 2-20-62

For $T_p = 240^\circ F \equiv 700^\circ R$

	$(\Delta T)_p$	T_f °F	T_f °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
Table T ₂	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 $T_p = 600^\circ F \equiv 1060^\circ R$

	$(\Delta T)_p$								h_r	
	50	130	590	5.9	5.4	11.3	34.81	29.16	63.97	1.13
Table T_3	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 $T_p = 400^\circ F \equiv 860^\circ R$

	$(\Delta T)_p$									h_r
	50	450	910	9.1	8.6	17.7	82.81	73.96	156.77	4.34
Table	100	500	960	9.6	"	18.2	92.16	"	166.12	4.75
T ₄	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 $T_p = 800^\circ F \equiv 1260^\circ R$

	$(\Delta T)_p$									h_2
Table T ₅	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

REFERENCE:

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DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 7

At a Backus 2-20-62

$(\Delta T)_s$

1200

1000

800

600

400

200

0

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

$h_c + h_r$
= 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
@ $T_p = 80^\circ$

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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DRAWING NO.

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FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 8

H.A. BACKUS 2-6-62

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 R values is given in both Marks and Mc Adams 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 cask in the fire test, we are attempting to establish the unwritten but implied specifications of the "furnace" which is to heat our cask, 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 & cask seem appropriate.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 9

At a Backus 2-20-62

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.

$(\Delta T)_p = (h_r) + (h_c + h_r) \text{ marks}$		$1/2" \text{ I.P.S.} = h_c$		$4" \text{ I.P.S.} = h_c$		$24" \text{ I.P.S.} = h_c$		$\text{VERT PLATE} = h_c$	
Table	T_3								
	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			
Table	200	1.68	3.10 1.42	2.72 1.04	2.45 .77	2.70 1.02			
H_1	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	10.28 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.

$(\Delta T)_p$ h_r 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	T_3								
	50	1.13	2.26 1.13	2.05 .92	1.95 .82	1.87 .74			
H_2	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 1.57

FIGURE 2 INITIAL VALUES OF h_c and h_r for body at 80°F

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 10

Atg Backus 2-20-62

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 $\frac{1}{2}$ " 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 $600^\circ F = (\Delta T)_p$,

$$h_c = \frac{1.05}{D^{1/4}} + \frac{600}{800} = \frac{1.05}{D^{1/4}} + .75$$

$$h_c \text{ for } \frac{1}{2}" \text{ I.P.S.} = \frac{1.05}{(\frac{1}{2})^{1/4}} + .75 = \frac{1.05}{.84} + .75 = 1.25 + .75 = \underline{2.0}$$

$$\text{while } h_r = \underline{4.20} \quad \frac{h_c}{h_r} = \frac{2.0}{4.20} = \underline{.476}$$

$$\text{and } (h_c + h_r) = 6.20 = \underline{1.475 h_r}$$

$$h_c \text{ for } 55" \text{ pipe} = \frac{1.05}{55^{1/4}} + .75 = \frac{1.05}{2.733} + .75 = .38 + .75 = \underline{1.13}$$

$$h_r = 4.20 \quad \frac{h_c}{h_r} = \frac{1.13}{4.20} = \underline{.269}$$

$$\text{and } (h_c + h_r) = 5.33 = \underline{1.27 h_r}$$

at $t_p = 80^\circ$ and $(\Delta T)_f = 1200^\circ F$

$$h_c = \frac{1.05}{D^{1/4}} + \frac{1200}{800} = \frac{1.05}{D^{1/4}} + 1.5 \quad (h_c + h_r) = \underline{1.23 h_r}$$

$$h_c \text{ for } \frac{1}{2}" \text{ I.P.S.} = 1.25 + 1.5 = 2.75$$

$$h_r = 11.85 \quad (h_c + h_r) = 2.75 + 11.85 = 14.60 \text{ (cf } 14.65 \text{ mark)} \quad \underline{1.23 h_r}$$

REFERENCE:

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DRAWING NO.

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

PAGE 11

H. Q. Backus 2-20-62

SUMMARY h_c and h_r

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 $q_p = \frac{\text{BTU}}{\text{hr.}}$ absorbed by body ($\frac{1}{2}$ " I.P.S pipe)

$h_c = \frac{\text{BTU}}{\text{hr ft}^2 \text{ } ^\circ\text{F}}$ coef. of convective heating - from furnace to pipe.

$h_r = \text{"}$ 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 cask, and none on the pipe, make $A_c = A_r$ for the pipe only.

$A_r =$ area subjected to radiant heating.

$(t_f - t_p) =$ differential temp. between "furnace" and body (pipe or cask)
mean values for each interval are used.

Expressing the radiant heating effect in this form, once the conversion is made from a T^4 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 ultimate 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.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 12

Of. G. Backus 2-20-62

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)

$(w \cdot C_p) = .851 \times .118 = .1004 \frac{\text{BTU}}{^\circ\text{F}}$

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 $\left(\frac{r_2}{r_1} = \frac{24.5}{1.5} = 1.63\right) = 1.02$ (Jakob PG-3)
 $\therefore$ wall can be calculated as a plane plate within 2% error.
 $\alpha = .80$ absorptivity of surface - gray painted steel - burned & oxidized
 $E = .80$ 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	$= 1445$	$= 1628 @ 0.37$
	<u>3965</u>	<u>4148</u>

Addition of 20,000 $\frac{\text{BTU}}{\text{hr}}$ during 1 hour test would $= \frac{20,000}{4148} = 14^\circ$ 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

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 13

FOOT OF WEST ST.

WILMINGTON, DEL.

St. G. Backus 2-20-62

Evaluation of A_c and A_r 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.

$$A_s = \text{area shell without fin base area.} \\ = (8 \text{ ft} \times \frac{\pi 49}{12}) - 72 \left(\frac{78.5}{12} \times \frac{1}{12} \right) = 102.5 - 9.8 = 92.7 \text{ ft}^2$$

$$A_F = \text{area fins} = 72 \left(\frac{78.5}{12} \times \frac{3+3+1}{12} \right) = 245 \text{ ft}^2$$

$$N = w \sqrt{\frac{h}{KY_0}} \quad (\text{Jakob p 235})$$

$$w = \text{fin width} = 3\frac{1}{2} \text{ ft.}$$

$$h = \text{film coef. assumed} = .60$$

$$K = \text{therm. conductivity of fin} = 26 \text{ at } 712^\circ \\ = 22 \text{ at } 932^\circ$$

$$Y_0 = \text{fin half thickness} \quad \text{assume average} = 24. \\ = \frac{1}{2} \times \frac{1}{12} = .0104 \text{ ft.}$$

$$N = .25 \sqrt{\frac{.60}{24(.0104)}} = .38$$

$$\eta = .95 \text{ from curve} = \tanh(N)$$

$$A_c = A_s + \eta_F A_F = 92.7 + .95(245) = 92.7 + 232.7 \\ = \underline{\underline{325.4 \text{ ft}^2}}$$

$$A_r = \left(\pi \frac{55}{12} \right) \times 8 \text{ ft} = \underline{\underline{115.5 \text{ ft}^2}}$$

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.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 14

H. G. Backus 2-20-62

DETERMINATION OF TIME-TEMP. CURVE FOR "STANDARD" FIRE.

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 $t_1, t_2, t_p, (T_p/100)^4$ are now calculated.

(3) assume a value for ΔT in $\Delta T = T_f - T_p$
and calculate $t_f, T_f \cdot (T_f/100)^4$

$$h_c = \frac{1.05}{D^{1/4}} + \frac{\Delta T}{800} \quad \text{as previously accepted}$$

$$h_r = \frac{\alpha \sigma}{\Delta T} (T_f^4 - T_p^4)$$

$$= \frac{.1566}{\Delta T} \left[\left(\frac{T_f}{100} \right)^4 - \left(\frac{T_p}{100} \right)^4 \right]$$

for the pipe $\alpha = .90$

$$\alpha \sigma T^4 = .1566 \left(\frac{T}{100} \right)^4 \quad \text{general for } T_f \text{ and } T_p$$

(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_p are determined correctly
and thus provide a point to help identify the desired curve.

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FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 15

Of. Q. Backus 2-20-62

Nomenclature

Q BTU.

$q = \frac{Q}{\text{HR.}}$ BTU/HR.

$h = \text{coef}$ BTU/HR·FT²·°F

$C_p = \text{coef.}$ BTU/lb °F

$H = \frac{q}{A}$ 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 $\rightleftharpoons$

f "FURNACE" (STD. TEST MODEL)

P PIPE (THERMOCOUPLE PROBE)

K CASK (TYPICAL HEAVY BODY)

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DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 16

Pl. G Back/MS 2-20-62

E and A
Iron and Steel (not including stainless) (McAdam)

- metallic surfaces or very thin oxide layer
- oxidized surfaces

FIGURE 3

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DRAWING NO.

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 FOOT OF WEST ST. WILMINGTON, DEL.

PAGE 17

10/9/62 2-20-62

THERMAL PROPERTIES OF LEAD AND STEEL

$$q = KA \frac{\Delta T}{\Delta x} = \text{BTU/hr}$$

1) Thermal conductivity $K = (\text{BTU/hr/ft/}^\circ\text{F}) \left[= \frac{\text{BTU./SQ.FT.} \times \text{ft.}}{\text{hr.} \times ^\circ\text{F}} \times \text{ft.} = \frac{\text{BTU/hr}}{\text{SQ.FT.} \times ^\circ\text{F}} \times \text{ft.} \right]$

ALUM	LEAD	STEEL	TEMP. °F	authority
115	21.		32	Jacob - Hawkins, Elements of Heat Transfer.
114	19		392	" " (from Navy and Br. 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	9.2	752	
	8.96	8.96	932	
	8.72	8.72	1292	" "

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DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 18

at a Backus 2-20-62

2) Specific heat c_p $\frac{\text{BTU.}}{(\text{lb})(^\circ\text{F})}$

LEAD	STEEL (mild)	STEEL (304)	AL	TEMP $^\circ\text{F}$
.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

.036

700 (molten) McAdams (from liquid - Metals HB)

.037

900

.037

952 (molten) Nuclear Engineering - Bonelli

.037

932 "

.116

.12

.22

212

" "

.23

212

ASME. - Code

3) Linear Expansion $\times 10^6 / ^\circ\text{F}$

6.5	8.0	13.1	212
6.5	9.61	13	
		13.5	
16.2		14.	
17.0	6.5	9.3	
	6.7	13.1	

Nuclear Engineering - Bonelli

Roark

ALCOA

Eshbach

K.A.P.L

ASME. - Code

4) Thermal Diffusivity α ft^2/hr

.37 $\times 10^{-13}$ $\times 0.32^\circ$ $\times 0.32^\circ$

Jakob

5) Density ρ lb/mft^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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DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 19

Of 9 Backus 2-20-62

Summary Tables of "Pipe" Calculations

Θ	$\delta\theta$	t_1	t_2	δt	$\overset{\text{mean}}{t_p}$	$\frac{T_p}{100}$	$(\frac{T_p}{100})^4$
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		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

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FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 21

of 9 Backus 2-20-62

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_r

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DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 22

FOOT OF WEST ST.

WILMINGTON, DEL.

By: A. Backus

2-20-62

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	1.5785	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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DRAWING NO.

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FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 23

Of 9 Pages 2-20-62

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 is mean value $= t_1 + \frac{\delta t}{2} = 68 + \frac{272}{2} = \underline{204^\circ F}$

$T_p = t_p + 460 = 664^\circ R$

$\left(\frac{T_p}{100}\right)^4 = 6.64^4 = 1944.$

$Q = (W.C_p) \delta t = (.851 \times 118) 272 = .100418 (272) = \underline{27.314 \text{ BTU}}$

$q = \frac{Q}{\delta \Theta} = \frac{27.314}{1/60} = \underline{1638.82 \text{ BTU/HR.}}$

$H = \frac{Q}{\delta \Theta \cdot A} = \frac{27.314}{1/60 \times 220} = \underline{7449 \text{ BTU/HR. FT}^2}$

$\Delta t = t_f - t_p$

$\therefore t_f = \Delta t + t_p$

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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FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 24

FOOT OF WEST ST.

WILMINGTON, DEL.

Atty. Backus 2-20-62

TRY $\Delta T = 743^\circ$

✓ $T_f = 743 + 204 = 947^\circ F$

$T_f = 947 + 460 = 1407^\circ R$ $\left(\frac{T_f}{100}\right)^4 = 14.07^4 = 39190.121$

$h_c = \frac{1.05}{D^W} + \frac{\Delta T}{800} = 1.25 + \frac{743}{800} = 1.25 + .9287 = 2.1787$

$h_r = \frac{.1566}{743} \left[\frac{39190.121 - \frac{1994}{37246.121}}{1} \right] = 7.8499$

$(h_c + h_r) = \frac{2.1787 + 7.8499}{10.0286} \therefore H = 10.0286 (743) = 7451$ OK.
(7449)

To shorten calculations, certain quantities can now be most directly calculated in tabular form. These are

$t_1, t_2, \delta T$ from curve of Standard Fire

T_p mean value $= t_1 + \frac{\delta T}{2}$

$T_p \quad \frac{T_p}{100} \quad \left(\frac{T_p}{100}\right)^4$

$H = \frac{q}{A \delta \theta} = \frac{(w \cdot c_p) \delta T}{A \delta \theta} = \left(\frac{w \cdot c_p}{A}\right) \frac{\delta T}{\delta \theta} = \left(\frac{100418}{.220}\right) \frac{\delta T}{\delta \theta}$
 $= 45644 \frac{\delta T}{\delta \theta}$

For intervals of $\frac{\delta \theta}{\text{only}} = \frac{1}{60}$ $H = 27.3864 \delta T$

$\theta = 2 \quad \delta T = 224 \quad t_1 = 340 \quad t_2 = 564 \quad T_p = 452 \quad \left(\frac{T_p}{100}\right)^4 = 6918$

$H = 27.3864 (224) = 6137.$

TRY $\Delta T = 503$

✓ $T_f = 503 + 452 = 955^\circ F$

$T_f = 955 + 460 = 1415^\circ R$ $\left(\frac{T_f}{100}\right)^4 = 14.15^4 = 40,089$

$h_c = 1.25 + \frac{503}{800} = 1.25 + .6287 = 1.8787$

$h_r = \frac{.1566}{503} \left(\frac{40089 - \frac{6918}{33171}}{1} \right) = \frac{10.3271}{12.2058} = (h_c + h_r)$

$H = (h_c + h_r) \Delta T = 12.2058 (503) = 6139.5$ OK.
> 6137

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 25

FOOT OF WEST ST.

WILMINGTON, DEL.

01.9.00/100 2-20-62

$$\theta = 3 \quad H = 4932 \quad x_p = 654$$

$$\text{TRY } \Delta T = 329.5 \quad x_f = 329.5 + 654 = 983.5$$

✓

$$T_f = 983.5 + 460 = 1443.5$$

$$14.435^4 = 43417.7$$

$$h_c = 1.25 + \frac{329.5}{800} = \frac{1.25}{.4118} = \frac{1.6618}{1.6618} = 1.6618$$

$$h_r = \frac{.1566}{329.5} \left(\frac{43417.7}{-15400} \right) = \frac{13.3155}{14.9773} = h_c + h_r$$

$$H = 14.9773 (329.5) = \underline{4935} \quad \text{OK} > 4932$$

$$\theta = 4 \quad H = 3890$$

$$\text{TRY } \Delta T = 215^\circ$$

✓

$$x_f = 215 + 815 = 1030$$

$$T_f = 1490^\circ R \quad 14.9^4 = 49,284$$

$$h_c = 1.25 + \frac{215}{800} = \frac{1.25}{.2685} = \frac{1.5185}{1.5185}$$

$$h_r = \frac{.1566}{215} \left[\frac{49284}{-26426} \right] = \frac{16.6491}{18.1676} = h_c + h_r$$

$$H = 18.1676 (215) = \underline{3906} \quad \text{OK} > 3890$$

$$\theta = 5 \quad H = 3123$$

$$\text{TRY } \Delta T = 145$$

✓

$$x_f = 145 + 943 = 1088$$

$$T_f = 1548$$

$$15.48^4 = 57,422$$

$$h_c = 1.25 + \frac{145}{800} = \frac{1.25}{.181} = \frac{1.431}{1.431}$$

$$h_r = \frac{.1566}{145} \left(\frac{57,422}{-38,746} \right) = \frac{20.170}{21.601}$$

$$H = 21.601 (145) = 3132 \quad \text{OK} > 3123$$

$$\theta = 6 \quad H = 2466$$

$$\text{TRY } \Delta T = 100 \quad x_f = 100 + 1045 = 1145 = 1605 R$$

✓

$$h_c = 1.25 + \frac{100}{800} = 1.375$$

$$16.05^4 = 66,359$$

$$h_r = \frac{.1566}{100} \left(\frac{66359}{-51303} \right) = \frac{23.577}{24.952}$$

$$\times 100 = 2495 \quad \text{OK} > 2466$$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 26

of A Backus 2-20-62

$$\Theta = 7 \quad H = 1972$$

$$\text{TRY } \Delta T = 70 \quad T_f = 70 + 1126 = 1196 = 1656^\circ R$$

$$\checkmark h_c = 1.25 + \frac{70}{800} = \frac{1.25}{.087} \quad 16.56^4 = \underline{75,204}$$

$$h_r = \frac{.1566}{70} \left(\frac{75,204}{-63,272} \right) = \frac{26.591}{27.928} \quad \times 70 = \underline{1955} < 1970 \quad \text{OK}$$

$$\Theta = 8 \quad H = 1590$$

$$\text{TRY } \Delta T = 52 \quad T_f = 52 + 1191 = 1243 = 1703^\circ R$$

$$\checkmark h_c = 1.25 + \frac{52}{800} = \frac{1.25}{.065} \quad 17.03^4 = \underline{84,112}$$

$$h_r = \frac{.1566}{52} \left(\frac{84,112}{-74,300} \right) = \frac{29.549}{30.864} \quad \times 52 = \underline{1604} > 1590 \quad \text{OK}$$

$$\Theta = 9 \quad H = 1260$$

$$\text{TRY } \Delta T = 37.5 \quad T_f = 37.5 + 1243 = 1280.5 = 1740.5^\circ R$$

$$\checkmark h_c = 1.25 + \frac{37.5}{800} = \frac{1.25}{.0468} \quad 17.405^4 = \underline{91,769}$$

$$h_r = \frac{.1566}{37.5} \left(\frac{91,769}{-84,112} \right) = \frac{31.9756}{33.2724} \quad \times 37.5 = \underline{1248} < 1260 \quad \text{OK}$$

$$\Theta = 10 \quad H = 931$$

$$\text{TRY } \Delta T = 26.5 \quad T_f = 26.5 + 1283 = 1309.5 = 1769.5^\circ R$$

$$\checkmark h_c = 1.25 + \frac{26.5}{800} = \frac{1.25}{.033} \quad 17.695^4 = \underline{98,040}$$

$$h_r = \frac{.1566}{26.5} \left(\frac{98,040}{-92,297} \right) = \frac{33.937}{35.220} \quad \times 26.5 = \underline{933} > 931 \quad \text{OK}$$

$$\Theta = 11 \quad H = 740$$

$$\checkmark \text{TRY } \Delta T = 20 \quad T_f = 20 + 1315.5 = 1335.5 = 1793.5^\circ R$$

$$h_c = 1.25 + \frac{20}{800} = 1.275 \quad 17.935^4$$

$$h_r = \frac{.1566}{20} \left(\frac{103,468}{-98,929} \right) = \frac{35.540}{36.815} \quad \times 20 = \underline{736.30} < 740 \quad \text{OK}$$

$$\Theta = 12 \quad H = 603$$

$$\text{TRY } \Delta T = 16 \quad T_f = 16 + 1338 = 1354 = 1814^\circ R \quad 18.14^4 = 108,280$$

$$\checkmark h_c = 1.25 + \frac{16}{800} = 1.270$$

$$h_r = \frac{.1566}{16} \left(\frac{108,280}{-104,510} \right) = \frac{36.898}{38.168} \quad \times 16 = \underline{610.7} > 603 \quad \text{OK}$$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 27

FOOT OF WEST ST.

WILMINGTON, DEL.

OKA. B. B. B. 2-20-62

$$\Theta = 13 \quad H = 520 \quad T_f = 13 + 1358.5 = 1371.5 = 1831.5 R$$

$$\text{TRY } \Delta T = 13$$

$$18.315^4 = 112,519$$

$$\checkmark h_c = 1.25 + \frac{13}{800} = 1.25 + 0.01625 = 1.266$$

$$h_r = \frac{.1566}{13} \left(\frac{112,519}{-109,359} \right) = \frac{38.065}{39.331} \times 13 = 511.3$$

$$\Theta = 14 \quad H = 466$$

$$\text{OK} < 520$$

$$\text{TRY } \Delta T = 11.5 \quad T_f = 11.5 + 1376.5 = 1388 = 1848 R$$

$$18.48^4 = 116,629$$

$$\checkmark h_c = 1.25 + \frac{11.5}{800} = \frac{1.25}{.0143} = 1.2643$$

$$h_r = \frac{.1566}{11.5} \left(\frac{116,629}{-113,753} \right) = \frac{39.163}{40.4273} \times 11.5 = 464.9 \quad \text{OK} < 466$$

$$\Theta = 15 \quad H = 411$$

$$\text{TRY } \Delta T = 10 \quad T_f = 10 + 1392.5 = 1402.5 = 1862.5 R$$

$$\checkmark h_c = 1.25 + \frac{10}{800} = \frac{1.25}{.0125} = 1.2625$$

$$18.625^4 = 120,333$$

$$h_r = \frac{.1566}{10} \left(\frac{120,333}{117,770} \right) = \frac{40.1365}{41.3990} \times 10 = 414 \quad \text{OK} > 411$$

The remaining intervals are for $\Delta T = 15/60$ hrs. each

$$\Theta = 16-30 \quad H = 274$$

$$\text{TRY } \Delta T = 6 \quad T_f = 6 + 1475 = 1481 = 1941 R$$

$$19.41^4 = 141,939$$

$$\checkmark h_c = 1.25 + \frac{6}{800} = 1.25 + 0.0075 = 1.2575$$

$$h_r = \frac{.1566}{6} \left(\frac{141,939}{140,192} \right) = \frac{45.59}{46.848} \times 6 = 281 \quad \text{OK} > 274$$

$$\Theta = 31-45 \quad H = 160.5$$

$$\text{TRY } \Delta T = 3 \quad T_f = 3 + 1594 = 1597 = 2057 R$$

$$20.57^4 = 179,034$$

$$\checkmark h_c = 1.25 + \frac{3}{800} = 1.25 + 0.0037 = 1.2537$$

$$h_r = \frac{.1566}{3} \left(\frac{179,034}{177,992} \right) = \frac{54.3872}{55.6409} \times 3 = 166.9 \quad \text{OK} > 160$$

$$\Theta = 46-60 \quad H = 113$$

$$\text{TRY } \Delta T = 2 \quad T_f = 2 + 1669 = 1671 = 2131 R$$

$$21.31^4 = 206,221$$

$$h_c = 1.25 + \frac{2}{800} = 1.2525$$

$$h_r = \frac{.1566}{2} \left(\frac{206,221}{205,448} \right) = \frac{60.5259}{61.7784} \times 2 = 123.5 \quad \text{OK} > 113$$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 28

FOOT OF WEST ST.

WILMINGTON, DEL.

Go Backus

2-20-62

DETERMINATION OF TIME-TEMP. CURVE FOR CASK.

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

$$t_K, T_K, \left(\frac{T_K}{100}\right)^4 \text{ and } \Delta T_K \text{ for the cask.}$$

- (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 $\alpha C T^4$
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 it to 624° ,

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.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 29

OTA Backus 2-20-62

DIRECT RADIATION FROM "FURNACE"

The time rate of radiated energy from gray radiator is

$$(1) \quad \dot{q}_g = \epsilon_g \sigma A T^4$$

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)

$$(3) \quad Q = \alpha_c A_{rc} [\sum \sigma T_f^4 \times \text{HOURS}] \quad \text{This is found from curve for Furnace time-temp.}$$

Θ 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 × 411.623 = 6174.35	9672.081
30-45	15.97	20.57	179,034.	15 × 519.198 = 7787.97	17,460.051
45-60	16.71	21.31	206,221.	15 × 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.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 30

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2-20-62

TIME - TEMP. CURVES FOR FIRE AND CASK.

FIGURE 5

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 31

W. A. Backus 2-20-62

225000

200,000

 $(\frac{OB}{100})^4$

175,000

150,000

125,000

100,000

75,000

50,000

25,000

0 - - - - 12

B

24

MINUTES 36

48

60

T⁴ CURVESFIGURE GT⁴ - (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 T⁴)
(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)

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 32

HARBAUM 2-20-62

Summary Tables of Cask Calculations

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

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 33

J. A. Backus

2-20-62

Θ	δt	t_2	Δt	$\Delta t \delta \Theta$	$\delta \Theta$
1,2	7.9455	187.9455	767.028	25.5676	$\frac{2}{60}$
3,4	9.1425	197.088	814.4845	27.1494	$\frac{2}{60}$
5,6	11.9045	208.9925	913.462	30.4487	$\frac{2}{60}$
7,8,9	23.4244	232.4169	1018.2775	50.9138	$\frac{3}{60}$
10,11,12	28.1624	260.5793	1085.4831	54.2741	$\frac{3}{60}$
13,14,15	31.0863	291.6656	1110.8707	55.5435	$\frac{3}{60}$
16-30	178.749	470.4146	1100.1344	275.033	$\frac{1}{4}$
31-41.12	150.66	621.07	1040.2854	192.79	$\frac{11.12}{60}$
41.12-48.64	0	621.07	1017.	127.464	$\frac{7.53}{60}$
48.64-60	164.12	785.12	977.95	185.158	$\frac{11.36}{60}$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 34

Of a Backman

2-20-62

Θ	h_c	$h_c A_c$	h_r	$h_r A_r$	$(h_c A_c + h_r A_r)$	CONVECTIVE BTU $h_c A_c \cdot \Delta T_{\infty}$	NET RADIANT BTU $h_r A_r \cdot \Delta T_{\infty}$
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.
						2,859,387.03	
						TOTAL B.T.U. RECEIVED	
						@ $\alpha = .80$	

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 35

of 9 Pages

2-20-62

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 $\delta T = 10^\circ$

$$T_k = \text{mean temp. cook} = 180 + \frac{10}{2} = 185^\circ\text{F} = 645^\circ\text{R}$$

$$\left(\frac{T_c}{100}\right) = 6.45 \quad \left(\frac{T_c}{100}\right)^4 = 6.45^4 = 1730.768$$

$$\Delta T = 951 - 185 = 766^\circ \quad D = 55" \text{ dia} \quad D^{1/4} = 2.7233"$$

$$h_c = \frac{1.05}{D^{1/4}} + \frac{766}{800} = \frac{1.05}{2.7233} + 9.575 = .3855 + 9.575 = 1.3430$$

$$h_r = \frac{\alpha \sigma}{\Delta T} (T_f^4 - T_{\text{cook}}^4) \quad \alpha = .80 \quad \sigma = .174 \times 10^{-8}$$

$$\therefore h_r = \frac{.1392}{\Delta T} \left[\left(\frac{T_f}{100}\right)^4 - \left(\frac{T_k}{100}\right)^4 \right]$$

$$= \frac{.1392}{766} \left(\frac{39637}{37,907} \right) = 6.8885$$

$$q_c = h_c A_c \Delta T \quad \text{convective rate BTU/HR.}$$

$$= 1.3430 (325.4) 766 = 334,751$$

$$q_r = h_r A_r \Delta T \quad \text{radiant rate BTU/HR.}$$

$$= 6.8885 (115.5) 766 = 609,446$$

$$q = q_c + q_r = 944,197 \text{ BTU/HR.}$$

$$\delta T = \frac{q \cdot \delta T}{W \cdot Cp} = \frac{q}{30 \times 3965} = \frac{944,197}{118,950} = 7.937^\circ \quad \text{N.G. too low } < 10$$

TRY $\delta T = 7.944$

$$\checkmark T_k = 180 + \frac{7.944}{2} = 183.972^\circ\text{F} = 643.972^\circ\text{R} \quad 6.43972^4 = 1719.$$

$$\Delta T = 951 - 183.972 = 767.028$$

$$h_c = .3855 + \frac{767.028}{800} = \frac{.3855 + 958.7}{1.3442}$$

$$h_r = \frac{.1392}{767.028} \left(\frac{39637}{37918} \right) = 6.8813$$

$$q = (h_c A_c + h_r A_r) \Delta T$$

$$= [1.3442 (325.4) + 6.8813 (115.5)] \Delta T = (437.4 + 794.79) 767.028$$

$$= 1232.19 (767.028) = 945,124.231$$

$$\delta T = \frac{q}{30 \times 3965} = \frac{945,124.231}{118,950} = 7.9455^\circ \quad \text{OK}$$

$$T_2 = 180 + \delta T = 187.9455^\circ$$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 36

OK A. D. C. fur

2-20-62

$$\Theta = 3.4 \quad T_f = 1007 \quad T_{1, \text{ank}} = 187.9455$$

~~TRY~~ $\delta T = 8^\circ \quad T_c = T_1 + \frac{\delta}{2} = 191.9455 \quad \left(\frac{T_c}{100}\right)^4 = 6.5194^4 = 1806.4$

$$\Delta T = 1007 - 191.9455 = 815.0545$$

$$h_c = .3855 + \frac{815.0545}{800} = \frac{.3855}{1.0188} = 1.4043$$

$$h_2 = \frac{.1392}{815.0545} \left(\frac{46315}{-1806.4} \right) = 7.6014$$

$$\delta T = \left[1.4043(325.4) + 7.6014(115.5) \right] \frac{\Delta T}{30 \times 3965}$$

$$= \left[456.95 + 877.96 \right] \frac{815.0545}{118,950} = 9.1469^\circ \quad \text{N.B. too high}$$

~~TRY~~ $\delta T = 9.14 \quad T_c = T_1 + \frac{\delta}{2} = 187.9455$

$$\Delta T = \frac{1007}{-192.5755} = 814.4845 \quad \frac{4.57}{192.5755} \quad \left(\frac{T_c}{100}\right)^4 = 6.525155^4 = 1812$$

$$h_c = .3855 + \frac{814.4845}{800} = \frac{.3855}{1.018105} = 1.4036$$

$$h_2 = \frac{.1392}{814.4845} \left(\frac{46315}{1812} \right) = 7.6058$$

$$\delta T = \left[1.4036(325.4) + 7.6058(115.5) \right] \frac{\Delta T}{118,950}$$

$$= (456.73 + 878.47) \frac{814.4845}{118,950}$$

$$= 1335.20 \frac{814.4845}{118,950} = 9.1425^\circ \quad \text{OK}$$

$$T_2 = 187.9455$$

$$T_2 = 197.0880$$

$$\Theta = 5.6 \quad T_f = 1116.5$$

$$\checkmark \text{ TRY } \delta T = 11.9^\circ \quad T_c = 197.088 + 5.95 = 203.038$$

$$\Delta T = \frac{1116.5}{-203.038} = 913.462$$

$$h_c = .3855 \quad T_c = 663.038 \quad 6.63038^4 = 1932.6$$

$$\frac{1.14183}{1.52733} = \frac{913.462}{800}$$

$$h_2 = \frac{.1392}{913.462} \left(\frac{61770}{1932.6} \right) = 9.1184$$

$$\delta T = \left[1.52733(325.4) + 9.1184(115.5) \right] \frac{913.462}{118,950}$$

$$496.99 + 1053.17$$

$$1550.16$$

$$= 1550.16 \times \frac{913.462}{118,950} = 11.9045^\circ \quad \text{OK}$$

$$T_2 = \frac{197.088}{11.9045} = 208.9925^\circ$$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 37

FOOT OF WEST ST.

WILMINGTON, DEL.

AKA (Bulw) 2-20-62

$$\Theta = 7, 8, 9 \quad \tau_f = 1240 \quad \tau_1 = 208.9925$$

$$\text{TRY } \delta T = 19. \quad \tau_k = \tau_1 + 9.5 = 218.4925$$

$$T_k = 678.4925$$

$$6.784925^4 = 2119.$$

$$\Delta \tau = \frac{1240 - 218.4925}{1021.5075} \quad h_c = \frac{.3855}{1.2768} = \frac{1021.5075}{800}$$

$$h_2 = \frac{.1392}{1021.5075} \left(\frac{83521}{81402} \right) = 11.0925$$

$$\delta T = \left[1.6623(325.4) + 11.0925(115.5) \right] \frac{1021.5075}{20 \times 3965}$$

$$540.91 + 1281.18$$

$$1822.09$$

$$= \frac{1822.09(1021.5075)}{79,300} = 23.471^\circ$$

N.G.
too high

$$\text{TRY } \delta T = 23.46$$

$$\checkmark \quad \tau_k = 208.9925$$

$$\frac{12.73}{221.7225}$$

$$\left(\frac{T_k}{100} \right)^4 = 6.817225^4 = 2159.89$$

$$\Delta \tau = \frac{1240 - 221.7225}{1018.2775} \quad h_c = \frac{.3855}{1.2728}$$

$$1.6583$$

$$h_2 = \frac{.1392}{1018.2775} \left(\frac{83521}{81361.11} \right) = 11.1221$$

OK

$$\delta T = \left[1.6583(325.4) + 11.1221(115.5) \right] \frac{1018.2775}{79300} = 23.4244$$

$$539.61 + 1284.60$$

$$1824.21$$

$$\tau_2 = \frac{208.9925 - 23.4244}{232.4169}$$

$$\Theta = 10, 11, 12 \quad \tau_f = 1332$$

$$\text{TRY } \delta T = 35^\circ \quad \tau_k = \tau_1 + 17.5 = 249.9169$$

$$T_k = 709.9169$$

$$7.099169^4 = 2545.$$

$$\Delta \tau = \frac{1332 - 249.9169}{1082.0831} \quad h_c = \frac{.3855}{1.3526}$$

$$1.7381$$

$$h_2 = \frac{.1392}{1082.0831} \left[\frac{103,122}{100,577} \right] = 12.9383$$

N.G.

$$\delta T = \left[1.7381(325.4) + 12.9383(115.5) \right] \frac{1082.0831}{20 \times 3965} = 28.18$$

$$565.57$$

$$1494.37$$

$$2059.94$$

below

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 38

FOOT OF WEST ST.

WILMINGTON, DEL.

Sta Backm 2-20-62

$$7.065169^4 = 2491.66$$

$$\Delta t = \frac{1332. - 246.5169}{1085.4031} \quad h_c = \frac{.3855}{1.3560}$$

$$h_2 = \frac{.1392}{1085.4831} \left[\frac{103122.249166}{100,630.34} \right] = 12.9045$$

$$\delta T = \left[1.7423 (325.4) + 12.9045 (115.5) \right] \frac{1085.4831}{79300} = 28.1624$$

$$\frac{566.94}{1490.47} \quad t_2 = \frac{232.4169}{28.1624}$$

$$\Theta = 13, 14, 15 \quad \mathcal{L}_f = 1387.$$

$$\delta\theta = 1/20 \text{ HR}$$

$$\text{TRY } \delta T = 33 \quad T_c = \frac{260.5793}{16.5} \quad \left(\frac{T_c}{100}\right)^4 = 7.370793^4 = 2951.6$$

$$\Delta t = \frac{1387. - 277.0793}{1109.9207} \quad h_c = \frac{.3855 - 1.3874}{1.7729}$$

$$h_2 = \frac{.1392}{1109.9207} \left[\frac{116,377. \quad}{2951.6} \right] = 14.2252$$

$$\delta T = \left[1.7729 (325.4) + 14.2252 (115.5) \right] \frac{1109.9207}{79300} = 31.0708$$

Too low

TRY $\delta t = 31.1$

$$t_k = \frac{260.5293}{\frac{15.55}{276.1293}} \quad \left(\frac{t_k}{100}\right)^4 = 7.361293^4 = \underline{2936.4}$$

$$\Delta t = \frac{1387. - 276.1293}{1110.8707} \quad h_c = \frac{.3855 - .3886}{1.7741}$$

$$h_n = \frac{.1392}{1110.8707} \left(\frac{116,377.}{2936.4} \right) = 14.2149$$

$$\delta T = \left[\frac{1.7741(325.4) + 14.2149(115.5)}{\frac{577.29}{1641.82} + \frac{2219.11}{79300}} \right] \frac{1110.8705}{79300} = 31.0863$$

$$\tau_1 = 260.5793$$

$$\delta t = \underline{31.0863}$$

$$t_2 = 291.6656$$

$$\Theta = 16-30 \quad \tau_f = 1481 \quad \delta\theta = 1/4 \text{ HR.}$$

~~TRY~~ $\delta t = 193 \quad \tau_k = \left\{ \begin{array}{l} 291.6656 \\ 91.5 \\ 383.1656 \end{array} \right. \quad \left(\frac{\tau_k}{100} \right)^4 = 8.431656^4 = \underline{5054.19}$

$$\Delta t = \frac{1481 - 383.1656}{1097.8344} \quad h_c = \frac{.3855}{1.3723 / 1.7578}$$

$$h_2 = \frac{.1392}{1097.8344} \left[\frac{141,939.}{5054.19} \right] = 17.3563 \quad \text{N.G.}$$

$$\delta t = \left[\frac{571.98}{2004.65} + 17.3563(115.5) \right] \frac{1097.8344}{4 \times 3965} = 178.35 \quad \text{too low}$$

~~TRY~~ $\delta t = 178.4 \quad \tau_k = \left\{ \begin{array}{l} 291.6656 \\ 89.2 \\ 380.8656 \end{array} \right. \quad \left(\frac{\tau_k}{100} \right)^4 = 8.408656^4 = 4999.27$

$$\Delta t = \frac{1481 - 380.8656}{1100.1344} \quad h_c = \frac{.3855}{1.3751 / 1.7606}$$

$$h_2 = \frac{.1392}{1100.1344} \left[\frac{141939}{4999.27} \right] = 17.3270 \quad \text{OK}$$

$$\delta t = \left[\frac{572.9}{2001.2} + 17.327(115.5) \right] \frac{1100.1344}{15860} = 178.749$$

$$\tau_k = \left\{ \begin{array}{l} 291.6656 \\ 178.749 \\ 470.4146 \end{array} \right.$$

$\Theta = 31-41.12$ This interval brings the cook up to 621 °F only

~~TRY~~ 10 min interval
 $\tau_f = 1584 \quad \left(\frac{\tau_f}{100} \right)^4 = 20.44^4 = \underline{174,551.1}$

~~TRY~~ $\delta t = 621 - 470.4 = \underline{150.6}$

$$\tau_k = \left\{ \begin{array}{l} 470.4146 \\ 75.3 \\ 545.7146 \end{array} \right. \quad \left(\frac{\tau_k}{100} \right)^4 = 10.057146^4 = \underline{10,230.5}$$

$$\Delta t = \frac{1584 - 545.7146}{1038.2854} \quad h_c = \frac{.3855}{1.2978 / 1.6833}$$

$$h_2 = \frac{.1392}{1038.2854} \left(\frac{174,551.1}{10,230.5} \right) = 22.0313 \quad \text{N.G.}$$

$$\delta t = \left[\frac{547.74}{3092.35} + 22.0313(115.5) \right] \frac{1038.2854}{60\% \times 3965} = \underline{134.961}$$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 40

OK'd Backward 2-20-62

TRY 11.12 MIN. Interval (30-41.12 min)

$$T_f = 1584 + 2 = 1586 \quad \left(\frac{T_f}{100}\right)^4 = 20.46^4 = 175,235.8$$

TRY $\delta T = 150.6$

$$\Delta T = \frac{1586}{\frac{545.7146}{1040.2854}} \quad h_c = \frac{.3855}{\frac{1.3003}{1.6858}}$$

$$h_2 = \frac{.1392}{1040.2854} \left[\frac{175,235.8}{10,230.5} \right] = 22.0792$$

$$\delta T = \left[\frac{1.6858(325.4)}{548.55} + 22.0792(115.5) \right] \frac{1040.2854}{\frac{60}{11.12} \times 3965} = 150.66 \quad \text{OK}$$

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

$$44,000 \# \times 9.8 \text{ BTU/LB} = 431,200 \text{ BTU}$$

$$\text{and this will take approx. } \frac{431,200}{53,722} = 8 \text{ min.}$$

$$\Theta = 41.12 - 48.64$$

Try an interval of 7.52 min.

$$\begin{aligned} T_f &= 1638 & = 2098^\circ R & 20.98^4 = 193,741 \\ \checkmark T_k &= 621 & = 1081^\circ R & 10.81^4 = 13,655 \end{aligned}$$

$$\Delta T = 1638 - 621 = 1017$$

$$h_c = \frac{.3855}{\frac{1.2712}{1.6567}} \quad h_2 = \frac{.1392}{1017} \left(\frac{193,741}{180,088} \right) = 24.648$$

$$q = \left[\frac{1.6567(325.4)}{539.09} + 24.648(115.5) \right] 1017 = 3,443,490 \text{ BTU/HR} = 57,391.5 \text{ BTU/MIN.}$$

$$\frac{431,200}{57,391.5} = 7.52 \text{ min} \quad \text{OK}$$

$$Q_r = \frac{41.12}{7.52} = 48.64 \quad \checkmark$$

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.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 41

A.G. Backus 2-20-62

$\Theta = 48.64 - 60.$ $T_f = 1681$ A new (w.c.p) = 4148 is now used for the steel and molten lead.

~~TRY~~ $\delta T = 163.5$ $T_K = 621 + 81.75 = 702.75 = 1162.75 R$
 $11.6275^4 = 18,278.6$

$\Delta T = 1681 - 702.75 = 978.25$

$h_c = \frac{.3885}{\frac{1.2228}{1.6083}}$ $h_r = \frac{.1392}{978.25} \left(\frac{210,119.6}{-18,278.6} \right) = 27.298$
 $191,841.$

$q = [1.6083(325.4) + 27.298(115.5)] 978.25 = 3,596,242.$

$\begin{array}{r} 523.3 \\ 3152.9 \\ \hline 3676.2 \end{array}$

$\delta T = \frac{3,596,242}{4148} \times \frac{11.36}{60} = 164.148$

Too High.

TRY 164.1 $T_K = 621 + 82.05 = 703.05$

$T_K = 1163.05$

$11.6305^4 = 18,247.4$

✓ $\Delta T = 1681 - 703.05 = 977.95$

$h_c = \frac{.3855}{\frac{1.2224}{1.6079}}$ $h_r = \frac{.1392}{977.95} \left(\frac{210,119.6}{-18,247.4} \right) = 27.303$
 $191,822.2$

$q = [1.6079(325.4) + 27.303(115.5)] 977.95 = 3,595,628.7$

$\begin{array}{r} 523.2 \\ 3153.5 \\ \hline 3676.7 \end{array}$

$\delta T = \frac{3,595,628.7}{4148} \times \frac{11.36}{60} = 164.12$

δK

$T_2 = 621 + 164.12 = 785.12^\circ F$ final temp of cast, (mean)

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 42

DTA Backus

2-20-62

DEVELOPMENT OF δT IN TERMS OF Q

$$Q = q \delta \theta = H A \delta \theta = h \Delta t A \delta \theta = h A (\Delta t \delta \theta) \\ h_{\text{mean}} = \frac{Q_{\text{total}}}{A (\sum \Delta t \delta \theta)} = \frac{H}{\Delta t} = h_{\text{mean}} A (\sum \Delta t \delta \theta)$$

$$H = \frac{Q}{A \delta \theta}$$

$$Q = (w \cdot c_p) \delta T = (h_c A_c + \alpha h_r A_r) \Delta t \delta \theta$$

$$q = \frac{Q}{\delta \theta} = \frac{(w \cdot c_p) \delta T}{\delta \theta} = (h_c A_c + \alpha h_r A_r) \Delta t$$

$$\delta T = \frac{Q}{(w \cdot c_p)} = \frac{q \delta \theta}{(w \cdot c_p)} = \frac{(h_c A_c + \alpha h_r A_r) \Delta t \delta \theta}{(w \cdot c_p)}$$

$$= \frac{h_c A_c \Delta t \delta \theta}{(w \cdot c_p)} + \frac{\alpha h_r A_r \Delta t \delta \theta}{(w \cdot c_p)}$$

$$= (h_c A_c) \Delta t \left(\frac{\delta \theta}{(w \cdot c_p)} \right) + \frac{\alpha \sigma}{\Delta T} (T_f^4 - T_k^4) \frac{A_r \Delta t \delta \theta}{(w \cdot c_p)}$$

$$= (h_c A_c) \Delta t \left(\frac{\delta \theta}{(w \cdot c_p)} \right) + \alpha \sigma T_f^4 \frac{A_r \delta \theta}{(w \cdot c_p)} - \epsilon \sigma T_k^4 \frac{A_r \delta \theta}{(w \cdot c_p)}$$

$$= \frac{\delta \theta}{(w \cdot c_p)} \left[(h_c A_c) \Delta t + \alpha (\sigma T_f^4) A_r - \epsilon (\sigma T_k^4) A_r \right]$$

$$\therefore \delta T = \frac{1}{(\sum w \cdot c_p)} \left[\underbrace{A_c (\sum h_c \Delta t \delta \theta)}_{Q_{\text{convective absorbed}}} + \underbrace{\alpha A_r (\sum \sigma T_f^4 \delta \theta)}_{\substack{= 26,430 \\ \text{from table}}} - \underbrace{\epsilon A_r (\sum \sigma T_k^4 \delta \theta)}_{Q_{\text{reradiant emitted}}} \right]$$

+ $Q_{\text{direct radiant absorbed}}$

The second term is dominant.

Except for A_c and A_r values, the first and third terms can be conveniently expressed in terms of the second term. Thus, let

$$Q_{\text{total absorbed}}^{\text{not}} = A_c [K_1] (\sum \sigma T_f^4 \delta \theta) + \alpha A_r [K_2] (\sum \sigma T_f^4 \delta \theta) \\ \text{where } (\sum \sigma T_f^4 \delta \theta) = 26,430.$$

$\therefore$ It will be shown that

$$Q_{\text{BTU absorbed}} = (.06475 A_c + \alpha .9428 A_r) (26,430)$$

for any body heated in the "Standard" Fire.

Note - it is important to keep (α) in evidence and not to let it be buried and forgotten as a part of (h_r) .

$$h_r = \frac{\sigma}{\Delta T} (T_f^4 - T_k^4)$$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 43

Df. Q Backus 2-20-62

COEFFICIENTS ASSIGNED IN BASIC FORMULA FOR "STANDARD" FIRE.

The present cask may safely be taken as typical of a group of such designs. Accordingly its quantitative data is used to evaluate the general formula.

Total B.T.U	2,859,387.03	
Convective	556,880.56	$= (K_1) A_c (\sum T_f^4 \delta \theta) = .06475 (325.4) (26430)$
Radiant (net)	2,302,506.47	$= \alpha (K_2) A_n (\sum T_f^4 \delta \theta) = .9428 (115.5) (26430)$
Basic Direct Radiant	3,052,740.	$= \alpha A_n (\sum T_f^4 \delta \theta) = 1.00 (115.5) (26430)$

The basic formula is, therefore.

$$\textcircled{1} \quad Q = (.06475 A_c + \alpha .9428 A_n) (26430)$$

where α = absorptivity coeff.

A_c = effective area for convective heat absorption

A_n = " " " radiant " "

(26430) = $\frac{Q}{A}$ time integral for 1 hour of "standard" Fire.

By present example,

$\alpha = .80$, conservative, leading to max. temp. rise

$A_c = 325.4 \text{ ft}^2$

$A_n = 115.5 \text{ ft}^2$

$$Q = [.06475 (325.4) + .80 (.9428) (115.5)] 26430.$$

$$= (21.06965 + 87.11472) 26430.$$

$$= (108.18437) (26430) = 2,859,373 \text{ BTU (cf 2,859,387.03 above)}$$

$\textcircled{2}$ This quantity Q can now be successively applied to the three phases of the physical program of the heat test.

$$Q_1 = \text{BTU's required to raise the mean temperature of the cask to } 621^\circ, \text{ the melting point of the lead.}$$

$$= (W \cdot C_p) (621 - T_0)$$

Example $Q_1 = 3965 (621.07 - 180) = 1,748,842.55 \text{ BTU}$

any surplus goes next into melting the lead at constant temperature.

$$Q_2 = W_{\text{lead only}} \times 9.8 \text{ BTU/lb}$$

Example $Q_2 = 44000 \text{ lb} \times 9.8 \text{ BTU/lb} = 431,200 \text{ BTU}$

any further surplus continues to raise the temperature of the cask.

$$Q_3 = (W \cdot C_{p2}) (T_{\text{final}} - 621) \quad W \cdot C_{p2} = 4148 \text{ above } 621^\circ$$

Example $Q_3 = 679,345 = 4148 (T_{\text{final}} - 621)$

$$\therefore T_{\text{final}} = \frac{679,345}{4148} + 621 = 163.7 + 621 = 784.7^\circ$$

Compare 785.12° calculated.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 44

W.A. Backus

2-20-62

EFFECT OF REDUCED α

The cork has so far been considered to have $\alpha = .80$ and the final temperature ran up to 785.12° in the calculated first test.

A value of .70 has been used in K.A.P.L. calculations for "unclean" steel. Substituting this lower value for α we have

$$Q = [0.06475(325.4) + .70(.9428)(115.5)] 26430$$

$$= (21.06965 + 76.7253) 26430$$

$$= (97.79495) 26430 = 2,571,505 \text{ BTU.}$$

subtracting the same $Q_1 = -1,748,842$

and $Q_2 = -\frac{822,663}{431,200} \text{ BTU}$

leaves $Q_3 = 391,463 \text{ BTU}$

$$\therefore \text{a new } \underline{t_{\text{final}}} = \frac{391,463}{4148} + 621 = 94.37 + 621 = \underline{715.37^\circ}$$

or about 70° reduction.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 45

W. A. Backus 2-20-62

STRESS CONDITIONS DURING FIRE TEST.

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.

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.

$$\begin{aligned}
 Vol &= \frac{\pi}{4} (47^2) \times 92.62 - \frac{\pi}{4} (31^2) \times 85.62 \\
 &= 1735 \times 92.62 - 755 \times 85.62 \\
 &= 160,695 - 64,643 = \frac{96,052 \text{ in}^3}{\text{gross}} \\
 &\quad - \frac{1060 \text{ in}^3}{\text{void}} \\
 &\quad \underline{\underline{95,000 \text{ in}^3 \text{ Net lead volume.}}}
 \end{aligned}$$

$$\begin{aligned}
 \text{Void Volume} &= (2\pi \cdot 22) 7.66 \\
 &= \underline{\underline{1060 \text{ in}^3}}
 \end{aligned}$$

% Void/Volume

$$\text{Cask } \frac{1060}{95000} = .01115$$

$$\text{Closure } \frac{130}{10210} = .01273$$

Volume of lead in closure head

$$\begin{aligned}
 &\frac{14 \times 4 \frac{1}{4}}{2} \times 2\pi 11.75 = 2190 \text{ in}^3 \\
 &\pi 23^2 \times 4 = 6650 \\
 &\pi 13.75^2 \times 2 \frac{1}{2} = \frac{1500}{10,340 \text{ in}^3} \\
 &\text{VOID } \frac{4 \times 1}{2} \times 2\pi 10.3 = \underline{\underline{130 \text{ in}^3}} \\
 &\quad \underline{\underline{10,210 \text{ in}^3 \text{ Net lead volume}}}
 \end{aligned}$$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 46

of a Backus 2-20-62

Net Expansion Volume (head-Steel)

Temperature conditions

mean temperature of cask at start of fire test	180°F
[1] max. assumed normal temperature	475°F
	assumed max increase <u>300°</u>
[2] Max. Fire Test	785°
	assumed max increase <u>600°</u>

Expansion of lead and steel

$16.3 \times 10^{-6} / ^\circ\text{F}$	max for lead
$- 6.7 \times 10^{-6} / ^\circ\text{F}$	max for steel plate - low carbon, shell
$9.6 \times 10^{-6} / ^\circ\text{F}$	net linear coef of expansion
$3 \times 9.6 \times 10^{-6} / ^\circ\text{F}$	net volume " " " of cask materials

Increase in volume of lead (excess of lead over steel)

$$\Delta \text{Vol} = (3 \times 9.6 \times 10^{-6}) \times 300^\circ = .00864 \text{ Vol} \quad \text{for [1] above cask and closure plate}$$
$$(\quad) \times 600^\circ = .01728 \text{ Vol} \quad \text{for [2] above}$$

Required Void Space

In closure head

$$10,210 \times .00864 = 88.2 \text{ m}^3 @ 300^\circ \quad \text{OK } 130 \text{ m}^3$$

$$10,210 \times .01728 = 176.4 \text{ m}^3 @ 600^\circ$$

This requires additional expansion of steel
to accommodate $176.4 - 130 = \underline{46.4 \text{ m}^3}$ expansion

In cask body

$$95,000 \times .00864 = 820.8 \text{ m}^3 @ 300^\circ \quad \text{OK } 1060 \text{ m}^3$$

$$95,000 \times .01728 = 1641.6 \text{ m}^3 @ 600^\circ$$

Expansion Volume Required

Temperature conditions

180°F mean temperature of cook 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

$$\begin{array}{rcl} 16.3 \times 10^{-6}/^{\circ}\text{F} & \text{max. value for lead} & \\ - 6.7 \times 10^{-6}/^{\circ}\text{F} & \text{max. value for steel} & \\ \hline 9.6 \times 10^{-6}/^{\circ}\text{F} & \text{Differential coeff. (lead-steel)} & \end{array} \left. \vphantom{\begin{array}{rcl} 16.3 \times 10^{-6}/^{\circ}\text{F} \\ - 6.7 \times 10^{-6}/^{\circ}\text{F} \\ \hline 9.6 \times 10^{-6}/^{\circ}\text{F} \end{array}} \right\} \text{Linear coeff.}$$

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

$$10,210 \text{ m}^3 \times .00864 = 88.2 \text{ m}^3 \quad \text{OK Void} = 130 \text{ m}^3$$

Cook Body

$$95000 \text{ m}^3 \times .00864 = 820.8 \text{ m}^3 \quad \text{OK Void} = 1060 \text{ m}^3$$

For 605° = Δt_2 and including growth on melting

Closure Head

$$3(9.6 \times 10^{-6}) \times 605^{\circ} = .017424$$

$$\begin{array}{r} 3.6\% \text{ volume} \\ \text{change on melting} = .036 \\ \hline .053424 \end{array}$$

$$\begin{array}{r} 10,210 \text{ m}^3 \times .053424 = 545.4 \text{ m}^3 \\ - 130. \text{ m}^3 \text{ Void} \\ \hline 415.4 \text{ m}^3 \end{array}$$

shell expansion required

Cook Body

$$\begin{array}{r} 95000 \text{ m}^3 \times .053424 = 5075 \text{ m}^3 \\ - 1060 \text{ m}^3 \text{ Void} \\ \hline 4015 \text{ m}^3 \end{array}$$

shell expansion required

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 48

OK Backman

2-20-62

Fire Test Expansion of Outer Shell

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 compressive 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.

$$\text{Hoop Stress} = \frac{1000 \times 15.5 \text{ "R}}{t = \frac{1}{2} \text{ "}} = 31,000 \text{ psi (nominal y.p.)}$$

The backup action of the basket in the region where the thickness is reduced to $t = \frac{1}{2} \text{ "}$ 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 cylinders 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

$$\text{Hoop stress} = 30,000 \text{ psi} = \frac{P \times 47/2}{t = 1 \text{ "}}$$

$$P = 30,000 \times 1 \times \frac{2}{47} = 1276 \text{ psi}$$

Therefore, plastic failure - or at least, plastic distortion of the flat plate areas can be expected before the outer wall will stretch.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 49

HAZARDUM 2-20-62

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 tank 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 - 8)

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 load 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:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED

PAGE 50

FOOT OF WEST ST.

WILMINGTON, DEL.

OK'D. B. P. 2-20-62

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 in^3 displacement.

Excess volume to be developed per inch of cylinder length is

$$\frac{4015 \text{ in}^3}{80"} = 50.2 \text{ in}^3/\text{in}$$

Present I.D. = 47" with area = 1735 in^2

at a temperature of 785° this I.D. has expanded to

$$47(1 + 605 \times 6.7 \times 10^{-6}) = 47(1 + .004355) = 47.2047"$$

with an area of $1750. \text{ in}^2$

$$\frac{50.2 \text{ in}^2}{1800.2 \text{ in}^2} \text{ is the required increase in area}$$

$$= \frac{1}{4} (47.875)^2$$

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 in^3 . The following study was made for the 46" I.D. lower flat plate. As a simplified model, from which 371 in^3 was expected, it shows, to scale, only .678" center deflection required.

For the upper plate, 1" thick, 371 in^3 are provided by this deflection at a pressure of 412 psi, and approx the full 415.4 in^3 at 460 psi, (hydraulic pressure).

It is concluded that the cask design is safe during the fire test.

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 51

Harbarkus 2-20-62

$$y \text{ at any radius } r = y_{\max} \times \left[\frac{(a^2 - r^2)^2}{a^4} \right] \text{ where } a = 23", a^2 = 529, a^4 = 279,841$$

$$\frac{y}{y_{\max}} = \frac{(a^2 - r^2)^2}{a^4} = \frac{(529 - r^2)^2}{279,841}$$

$$\text{let } r = 0 \quad \frac{y}{y_{\max}} = \frac{529^2}{279,841} = 1$$

$$y = 1 \times .678 = .678"$$

$$r = 5 \quad = \frac{(529 - 25)^2}{279,841} = \frac{254,016}{279,841} = .907$$

$$y = .907 \times .678 = .615"$$

$$r = 10 \quad = \frac{(529 - 100)^2}{279,841} = \frac{184,041}{279,841} = .657$$

$$y = .657 \times .678 = .446"$$

$$r = 15 \quad = \frac{(529 - 225)^2}{279,841} = \frac{97,416}{279,841} = .33$$

$$y = .33 \times .678 = .224"$$

$$r = 17 \quad = \frac{(529 - 289)^2}{279,841} = \frac{57,600}{279,841} = .206$$

$$y = .206 \times .678 = .140"$$

$$r = 20 \quad = \frac{(529 - 400)^2}{279,841} = \frac{16,641}{279,841} = .0595$$

$$y = .0595 \times .678 = .040"$$

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	$.335 \times 5 = 1.675$	$\frac{3.12}{4.45} \times 2.5 + 10.0 = 2.09 + 10 = 12.09$	20.22
4	$.182 \times 2 = .364$	$\frac{1.96}{2.20} \times 1.0 + 15 = .875 + 15 = 15.875$	5.77
5	$.088 \times 3 = .264$	$\frac{1.07}{1.40} \times 1.5 + 17 = 1.15 + 17 = 18.15$	4.80
6	$.04 \times 1 = .04$	$\frac{.04}{.04} \times 1 = 1$	.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:

FIRE TEST ANALYSIS

DRAWING NO.

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

PAGE 52

H. A. B. 2-20-62

Flat Plate (Rank, case 6, table X)
Edges fixed
uniform load over entire surface

$$y = -\frac{3W(m^2-1)}{16\pi E m^2 \lambda^3} \left[\frac{(a^2-r^2)^2}{a^2} \right] = \lambda \left[\frac{(a^2-r^2)^2}{a^2} \right] \quad \therefore \frac{y a^2}{\lambda} = (a^2-r^2)^2$$

Volume of space $V = \pi \int_0^{y_1} r^2 dy$ where $a \sqrt{\frac{y}{\lambda}} = a^2 - r^2$
 $r^2 = a^2 - \frac{a}{\sqrt{\lambda}} \sqrt{y}$

$$= \pi \int_0^{y_1} \left(a^2 - \frac{a}{\sqrt{\lambda}} y^{1/2} \right) dy$$

$$V = \pi \left(a^2 y_1 - \frac{a}{\sqrt{\lambda}} \frac{2}{3} y_1^{3/2} \right) = \pi \left(a^2 y_1 - \frac{a}{\sqrt{\lambda}} \frac{2}{3} y_1^{3/2} \right)$$

let $a = 23"$

$V = 370.8 \text{ in}^3$

$\lambda = 3/4"$

$$\lambda = \frac{-3W(m^2-1)}{16\pi E m^2 \lambda^3} = \frac{-3W \left[\left(\frac{1}{.30} \right)^2 - 1 \right]}{16\pi 29 \times 10^6 \left(\frac{1}{.30} \right)^2 \left(\frac{3}{4} \right)^3} = \frac{3W(10.11)}{1460 \times 10^6 (11.11)(.4218)}$$

$\therefore \lambda = .00442 W \times 10^{-6}$

$$V = \pi \left(529 y_1 - \frac{23}{.0665 \sqrt{W}} y_1^{3/2} \right) = 1660 y_1 - \frac{230,000 y_1^{3/2}}{\sqrt{W}}$$

let $V = 370.8 \text{ in}^3$

$$y_1 \text{ at center} = -\frac{3W(m^2-1)a^2}{16\pi E m^2 \lambda^3} = \lambda a^2$$

$$\therefore V = \pi \left(a^2 \lambda a^2 - \frac{a}{\sqrt{\lambda}} \frac{2}{3} (\lambda a^2)^{3/2} \right)$$

$$= \pi \left(a^4 \lambda - \frac{2}{3} \frac{a}{\sqrt{\lambda}} \lambda^{3/2} a^3 \right) = \pi a^4 \lambda - \pi \frac{2}{3} \lambda a^4 = \frac{\pi}{3} \lambda a^4$$

$$\therefore 370.8 = \frac{\pi}{3} (.00442 W \times 10^{-6}) 23^4$$

$$= .00467 W .2798 = .00128 W$$

$$\therefore W = \frac{370.8}{.00128} = 289,500$$

$$W = W \pi a^2 = W 1662$$

$$W = \frac{289,500}{1662} = 174 \text{ psi}$$

checking $\max y = -\frac{3(289,500) \left(\frac{1}{.32} - 1 \right) 23^2}{16\pi 29 \times 10^6 \frac{1}{.32} \left(\frac{3}{4} \right)^3} = \frac{4640 \times 10^6}{6840 \times 10^6} = .678"$

Case for $\lambda = 1"$ $W = \left(\frac{1}{.75} \right)^3 \times 174 \text{ psi} = 412 \text{ psi}$

$\lambda = 1\frac{1}{4}"$ $W = \left(\frac{1.25}{.75} \right)^3 \times 174 \text{ psi} = 806 \text{ psi}$

REFERENCE:

FIRE TEST ANALYSIS

DRAWING NO.

KNAPP MILLS INCORPORATED
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PAGE 53

OKA B. B. 2-20-62

PIQUA-ELK RIVER REACTORS SPENT FUEL SHIPPING CASK CRITICALITY ANALYSIS

I ARRANGEMENT OF FUEL ASSY'S IN CASK

THE FUEL ASSY'S ARE HELD IN 19 CAVITIES IN A SOLID ALUMINUM BASKET. CAVITIES ARE ON A 6" ϕ TO ϕ SPACING. DURING SHIPMENT NO WATER IS PRESENT. HOWEVER, DURING LOADING ALL SPACE NOT OCCUPIED BY ALUMINUM OR FUEL ASSEMBLY IS FILLED WITH WATER AT 70°F

II ANALYTICAL MODEL

AS A FIRST CONSERVATIVE APPROACH, ASSUME 19 NEW FUEL ASSY'S IN THE SAME ARRANGEMENT AS THE ACTUAL REACTOR IMMERSED IN COLD WATER. USE PHYSICS PARAMETERS OF ACTUAL CORE

(a) ELK-RIVER CASE

FINAL PHYSICS REPORT DATED 5/23/60
PAGE 2 INDICATES MINIMUM NUMBER
OF FUEL ASSEMBLIES REQ'D FOR
CRITICALITY IS 26. 10CFR 72.37 ALLOWS
SHIPMENT OF FUEL ASSY'S IF THE TOTAL
NUMBER OF ASSY'S IS LIMITED TO 75%
OF THAT REQ'D FOR CRITICALITY. IN THE

REFERENCE:
W-3100

PIQUA-ELK RIVER SPENT FUEL SHIPPING CASK

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

CRITICALITY ANALYSIS

DRAWING NO.

Page 1

ELK RIVER CASE 75% OF 26 = 19.5 AND
THE REQUIREMENT IS MET. THE K_{EFF} FOR
19 ELEMENTS UNDER IDEAL CONDITIONS IS

$$K_{EFF} = \frac{K_{\infty} e^{-\gamma B^2}}{1 + L^2 B^2}$$

FROM FINAL PHYSICS REPORT DATED 2/23/60 PAGE 6

$$\left. \begin{array}{l} \eta = 1.64 \\ \epsilon = 1.0 \\ f = 7.57 \\ p = .953 \end{array} \right\} K_{\infty} = 1.18$$

$$L^2 = 1.566$$

$$\gamma = 37.1$$

$$B^2 = \left(\frac{\pi}{H + 2R.S.} \right)^2 + \left(\frac{2.405}{R + R.S.} \right)^2$$

$$R.S. = 7.5 \text{ CM (REF START-UP PHYSICS REPORT 9/30/60)}$$

$$H = 152.4 \text{ CM}$$

$$R = \sqrt{\frac{N A}{\pi}} \quad \begin{array}{l} A = 111 \text{ CM}^2 \text{ PER DESY} \\ N = \text{NO. OF ELEMENTS} \end{array}$$

$$R = \sqrt{\frac{(19 \times 111)}{\pi}} = 25.4 \text{ CM}$$

$$B^2 = \left(\frac{\pi}{167.4} \right)^2 + \left(\frac{2.405}{33.4} \right)^2 = .00554$$

REFERENCE:

DRAWING NO.

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

PAGE 2

$$K_{\text{EFF}} = \frac{(1.18) e^{-(37.1)(.00554)}}{1 + (1.566)(.00554)} = 0.955$$

THIS IS COLD, CLEAN, NO BROWN PINS AND WITH NOMINAL 5" ϕ TO ϕ LATTICE SPACING IN WATER. CONSIDERING THAT THE ALUMINUM BASKET WILL DISPLACE ALL WATER BETWEEN FUEL ASSY'S AND THE SPACING WILL BE 6" ϕ TO ϕ ADEQUATE SAFETY MARGIN EXISTS. ALSO, REACTIVITY DECREASES WITH LIFETIME GIVING FURTHER SAFETY MARGIN FOR THE HEAVY FUEL LOAD.

(b) PIQUA CASE

FINAL PHYSICS REPORT FROM AI IS NOT YET AVAILABLE. HOWEVER, PHYSICS DATA * CONTAINED IN SECTION III OF OPERATING MANUAL DATED MARCH 1961 IS AS FOLLOWS:

$$\left. \begin{array}{l} \eta = 1.67 \\ \epsilon = 1.05 \\ f = 0.866 \\ \rho = 0.80 \end{array} \right\} K_{\infty} = 1.215$$

$$L^2 = 7.8$$

$$\tau = 62$$

$$\text{TEMP COEFFICIENT} = -7.5 \times 10^{-5} \frac{\Delta K}{K} / ^\circ F$$

* HOT, CLEAN CORE

REFERENCE:

DRAWING NO.

KNAPP MILLS INCORPORATED
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Page 3

CALCULATE K_{EFF} FOR 19 ASSEMBLIES UNDER ACTUAL CORE CONDITIONS

$$K = \sqrt{\frac{NA}{\pi}} \quad A = 202 \text{ CM}^2 \text{ PER ASSY}$$

$$B^2 = \left(\frac{\pi}{H + 2R.S.} \right)^2 + \left(\frac{2.405}{K + K.S.} \right)^2$$

USE R.S. = 10 $H =$

$$K = \sqrt{\frac{(19 \times 202)}{\pi}} = 11.5 \text{ CM}$$

$$B^2 = \left(\frac{\pi}{11.5} \right)^2 + \left(\frac{2.405}{45} \right)^2 = .00326$$

$$K_{EFF} = \frac{(1.215) e^{-(62 \times .00326)}}{1 + (7.8)(.00326)} = 0.968$$

APPROXIMATE CORRECTION TO COLD CONDITIONS

$$\Delta K = (7.5 \times 10^{-5}) (350)^* = .026$$

$$K_{EFF} \text{ COLD} \approx 0.994$$

THIS AGREES WELL WITH VERBAL COMMUNICATIONS WITH AI PERSONNEL AT PIQUA WHO PREDICT 20 ELEMENTS FOR CRITICALITY.

* APPLYING TEMPERATURE COEFFICIENT ONLY DOWN TO 200°F WHERE MAX REACTIVITY OCCURS (APPROX)

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PAGE 4

FURTHER ANALYSIS CONSIDERING ACTUAL MATERIALS. PRESENT IN THE CASK AND BASKET WILL BE REQ'D. IF THE K_{eff} CALCULATED UNDER THESE CONDITIONS IS LESS THAN 0.9 NO POISON WILL BE REQ'D. IF IT IS GREATER THAN 0.9, THREE POSSIBLE SOLUTIONS EXIST:

1. REDUCE NO. OF ASSY'S TO 75% OF THAT REQ'D FOR CRITICALITY (15-16 ASSY'S)
2. REQUEST WAIVER OF THE 10CFR 72 REQ'T OF $K_{eff} = 0.9$ MAX TO 0.95. THERE IS REASONABLE JUSTIFICATION FOR SUCH A REQUEST IN THIS CASE SINCE THE K_{eff} FOR 19 ELK RIVER ELEMENTS (75% OF 26) IS 0.95.
3. ADD POISON ELEMENT TO ALUMINUM BASKET. THIS MAY BE DONE BY USING BISON SET MECHANICALLY ATTACHED OR CADMIUM IN THE CASTING ALLOY.

IT IS POSSIBLE THAT THE K_{eff} UNDER ACTUAL CONDITIONS IN CASK WILL BE SUCH THAT POISON WILL NOT BE REQUIRED. THIS DETERMINATION WILL BE MADE AFTER THE DESIGN OF CASK AND BASKET IS FIRM AND PRELIMINARY DESIGN APPROVAL HAS BEEN OBTAINED IN ALL OTHER AREAS. THIS WILL PREVENT COSTLY RECALCULATION OF K_{eff} DUE TO DESIGN CHANGES.

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DRAWING NO.

PAGE 5

PIQUA-ELK RIVER REACTORS
SPENT FUEL SHIPPING CASK
LOADING AND UNLOADING PROCEDURES

I. INTRODUCTION

The spent fuel cask will be shipped to site by rail in a vertical position on its shipping structure. A 35 ton (min.) mobile crane and "low-boy" tractor trailer will be required to handle and transport the cask to the containment shell air lock. The special cask lifting gear will be shipped with the cask in separate containers.

II. SELF-BY-STEP PROCEDURES

a. Preparation for Loading

1. Attach two special lifting lugs to upper cask body, and one on lower cask body.
2. Using mobile crane and standard lifting slings, lift cask and shipping structure from rail car and place on low-boy.
3. Tie down and transport cask to containment shell.
4. Remove shipping structure "A-Frame" supports.

PIQUA

ELK RIVER

5. Lift cask from shipping structure and place in vertical position on loading platform outside airlock. 6. Washdown Cask Exterior 7. Using the upper cask lifting lug on the "W" axis, lift and tilt cask on its bottom corner opposite lifting lug. When C.G. of cask passes over bottom corner fulcrum point, lower cask into horizontal position on temporary blocks placed to prevent damage to cooling fins. 8. Attach standard slings to upper and lower lifting lugs on cask body and lift in horizontal position.	5. Lift cask from shipping structure and place in vertical position adjacent to monorail.

PIQUA

ELK RIVER

9. Place cask on dolly on	9. Place cask on blocks

REFERENCE:

W-3100

Piqua Elk River Spent Fuel Shipping Cask

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

DRAWING NO.

Page 1

loading platform

directly below monorail.
Attach monorail hooks to
upper and lower cask lift-
ing lugs lift cask to
building floor level roll
inside and place on dolly.

10. Open air lock doors and run cask into containment shell.
11. Attach slings to upper and lower cask lifting lugs. lift in horizontal position and place on floor on blocks.
12. Attach sling to upper cask lifting lug, lift and tilt cask on bottom corner opposite lifting lug. When full weight of cask is on 30 ton crane, attach 5 ton hoist to pull cask C.G. over bottom corner fulcrum point while keeping 30 ton cable tight. When C.G. passes over bottom corner, lower 30 ton crane until cask is in vertical position.
13. Remove cask closure head bolts and rupture disc assembly.
14. Attach four lifting lugs on closure head and one closure head guide on cask body.
15. Remove closure head.
16. Using special lifting adapter plate remove basket from cask.
17. Clean cask internal cavity.

PIQUA

ELK RIVER

18. Disassemble clean and reassemble basket with bottom corner protector segments	18. Disassemble clean and reassemble basket with bottom support plate
19. Carefully install basket in cask using special lifting adapter plate.	19. Carefully install basket in cask using special lifting adapter plate. Remove adapter plate and install upper fuel assembly support plate.

REFERENCE:

W-3100

Piqua Elk River Spent Fuel Shipping Cask

KNAPP MILLS INCORPORATED

FOOT OF WEST ST. WILMINGTON, DEL.

DRAWING NO.

Page 2

20. Check "O" ring seals in cask body. Replace if necessary.

b. Loading

1. Lift cask and lower into loading pool.
2. Carefully install nineteen fuel assemblies in the basket cavities.
3. Lift closure head and lower into loading pool. Visually guide closure head onto cask body until guides on closure head lifting lugs engage cask body.
4. Carefully lower closure head remaining distance allowing locating pins to orient closure head to cask body.
5. Detach slings from closure head and attach to upper cask lifting lugs.
6. Lift cask from pool, wash down exterior and allow to drip dry over loading pool.
7. Place cask on floor and connect portable potentiometer to four thermocouple junction boxes.
8. Drain water from cask through bottom drain valve; leave valve open. Siphon required to remove last bit of water from drain line.
9. Observe and record temperatures from four thermocouples. Plot curve of temperature vs. time to eventually show equilibrium conditions.
10. Open vent valve in closure head and install rupture disc assembly. Make certain vent valve remains open until equilibrium conditions are established.
11. Install closure head bolts and torque uniformly to _____ lb-ft alternating from side to side on the cask.
12. Remove four closure head lifting lugs and one closure head guide.
13. When equilibrium conditions have been established ascertain that maximum fuel temperatures will not exceed Elk River - 600° F. or Piqua - 700° F considering anticipated conditions over travel route.
(Performance data from test program and thermal design

REFERENCE:

W-3100

Piqua Elk River Spent Fuel Shipping Cask

KNAPP MILLS INCORPORATED

FOOT OF WEST ST. WILMINGTON, DEL

DRAWING NO.

Page 3

calculations will contain necessary information for this determination).

14. Close drain valve and using vent valve connection in closure head, ~~pressurize~~ cask to 10 PSI with air. Check seals, valves and fittings for leakage, using soap-bubble method.
15. Depressurize cask and sample exhausted air with air monitor to determine air activity is within allowable limits.
16. Close and plug vent valve and drain valve; lockwire valve hand wheels.
17. Smear test cask external surface to determine surface contamination is within allowable limits.
18. Handle cask into horizontal position, place on dolly and remove from containment shell using previously described procedures.
19. Place cask in its shipping structure and install "A-Frame" braces.
20. Transport to rail siding on low-boy and place cask and shipping structure on rail car.
21. Place all lifting lug and basket adapter components in storage boxes provided on shipping structure and prepare for shipment.
22. Tie down shipping structure to rail car per procedures approved by railroad inspector.
23. Prior to releasing for shipment ascertain that AEC and Bureau of Explosives have been supplied with all required information and shipment is cleared for transport. (Information is required 20 days in advance).

c. Preparation for Unloading

1. Attach two lifting lugs to upper cask body.
2. Remove shipping structure "A-Frame" braces.
3. Remove cask from rail car and place in receiving and washdown area. Washdown cask exterior.
4. Connect portable potentiometer to four thermocouple junction boxes and monitor temperatures.

REFERENCE:

W-3100

Liquid Elk River Spent Fuel Shipping Cask

KNAPP MILLS INCORPORATED

FOOT OF WEST ST.

WILMINGTON, DEL.

DRAWING NO.

Page 4

5. Remove plugs from drain and vent valve. Connect air sampling monitor to vent valve and connect steam supply hose to drain valve (steam supply 15 PSI max.)
6. Unlock and open vent valve. Open drain valve and admit steam just enough to force air sample into air sampling fitting for monitoring.
7. If air or steam activity is above allowable levels for venting to atmosphere, preparation for containing and condensing steam during cooldown must be made. Also, activity must be analyzed for presence of fission products which may indicate failed fuel elements.
8. Make certain cask is depressurized and remove rupture disc assembly.
9. Attach standard 1" flanged fitting with hose line in place of rupture disc assembly. Include thermocouple well in fitting for indicating steam temperature.
10. Connect vent line thermocouple to portable potentiometer.
11. Commence cooldown of cask and fuel assemblies by admitting steam through cask drain valve.
12. Observe and record temperatures indicated by four cask thermocouples and vent line thermocouple.
13. When cask thermocouples indicate 200°F or less and vent line thermocouple less than 250°F disconnect steam supply and connect pure water supply to cask drain valve. This operation must be completed as quickly as possible.
14. Without delay, complete cooldown of cask by admitting water to cask at a maximum rate of 5 GPM. Sample water during cooldown for fission product activity.
15. When vent line thermocouple and cask thermocouples indicate less than 100°F, shut off water supply and disconnect both supply and vent hoses. Using transparent hose, connect to drain valve, drain water from cask until level is below closure seal.
16. Remove closure head bolts and attach closure head lifting lugs.
17. Lower cask into unloading pool
18. Remove closure head.

REFERENCE:

W-310C

Liqua Elk River Spent Fuel Shipping Cask

KNAPP MILLS INCORPORATED

FOOT OF WEST ST. WILMINGTON, DEL.

DRAWING NO.

Page 5

19. Remove fuel assemblies individually and transfer to storage area for reprocessing.
20. Remove cask from unloading pool and place in washdown area.
21. Decontaminate cask and head externally. Flush internally until water activity level is within allowable limits.
22. Drain cask dry and replace closure head
23. Replace rupture disc assembly and close drain and vent valves.
24. Replace cask in shipping structure on rail car and install "A-frame" braces.
25. Remove cask and closure head lifting lugs and replace in storage box on shipping structure.
26. Return cask to shipper.

REFERENCE:

W-3100

Piqua Elk River Spen Fuel Shipping Cask

KNAPP MILLS INCORPORATED

FOOT OF WEST ST. WILMINGTON, DEL.

DRAWING NO.

Page 6

PIQUA-ELK RIVER REACTORS' SPENT FUEL SHIPPING CASK TEST PROGRAM

I GENERAL - TESTS WILL BE PERFORMED ON THE CASK ASSEMBLY TO ASSURE SHIELDING INTEGRITY, DEMONSTRATE SATISFACTORY ASSEMBLY OF COMPONENTS, CONFIRM THERMAL DESIGN CALCULATIONS AND ASSURE ADEQUATE SHUT-DOWN MARGIN WITH RESPECT TO CRITICALITY.

II SHIELDING TEST

THE CASK WALLS WILL BE PROBED UTILIZING KNAPP MILLS GAMMA PROBE TECHNIQUE. THIS INSPECTION WILL BE CONDUCTED IMMEDIATELY AFTER LEAD POURING AND PRIOR TO CASK MACHINING. THE TESTS UTILIZES A HIGH-ENERGY (2 MEV) GAMMA SOURCE AND A SCINTILLATION DETECTOR AND COUNTING SYSTEM WITH SPECTRUM ANALYZER AND MAGNETIC STYLUS STRIP CHART RECORDER. THE SOURCE IS COLLIMATED TO BEAM RADIATION RADially THROUGH THE CASK WALL TO THE DETECTOR CRYSTAL. THE SPECTRUM ANALYZER IS CALIBRATED AND SET TO COUNT ONLY UNCOLLIDED SOURCE ENERGY PHOTONS. BY THIS TECHNIQUE DETECTION OF VOIDS OR FLAWS IN THE CASK WALL EQUIVALENT TO 5% OF THE SHIELD THICKNESS IS POSSIBLE.

REFERENCE:
W-3100

PIQUA-ELK RIVER SPENT FUEL CASK

DRAWING NO.

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

TEST PROGRAM

PAGE 1

THE CASK BOTTOM AND CLOSURE HEAD WILL NOT BE INSPECTED SINCE THESE ARE NOT CRITICAL AREAS WITH RESPECT TO POURING SOUND LEAD SHIELDING. CAREFULLY CONTROLLED LEAD POURING OPERATIONS ASSURE SOUND SHIELDING IN LARGE OPEN AREAS SUCH AS THE CASK BOTTOM AND CLOSURE HEAD. DETAILED LEAD POURING AND GAMMA PROBING PROCEDURES WILL BE SUBMITTED PRIOR TO PERFORMING THE OPERATIONS. D

III MECHANICAL TESTS

AFTER COMPLETION OF ALL COMPONENT PARTS, ASSEMBLY TESTS WILL BE CONDUCTED TO DEMONSTRATE SATISFACTORY FIT OF MATING PARTS AND ADEQUACY OF ASSEMBLY EQUIPMENT AND PROCEDURES. PARTICULARLY IMPORTANT IS THE BASKET AND CLOSURE HEAD INSTALLATION OPERATIONS. ALSO, THE BASKET CAVITIES WILL BE CHECKED BY INSTALLING DUMMY FUEL ASSEMBLIES (TO BE FURNISHED BY DEC). TO INSURE ADEQUATE CLEARANCE AND NO INTERFERENCE, ALSO, WITH THE CASK COMPLETELY ASSEMBLED, A LEAK TEST AT 10 PSI WILL BE CONDUCTED. THIS WILL BE A SOAP-BUBBLE TEST AT ALL GASKETS, CLOSURE VALVES AND FITTINGS. PRESSURE TESTS TO ASME CODE REQUIREMENTS WILL BE PERFORMED DURING FABRICATION OF INTERNAL VESSEL AND CLOSURE HEAD.

REFERENCE:

DRAWING NO.

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

PAGE 2

LOAD ON THE CASK, THE EFFECTIVE LENGTH AND VERTICAL LOCATION OF THE HEATERS WILL BE BASED ON PIQUA CONDITIONS. THE HEAT LOAD WILL BE VARIED UP TO DESIGN CONDITIONS TO DEVELOP OPERATING DATA FOR FUTURE CASK USE. NO ATTEMPT WILL BE MADE TO SIMULATE RADIAL AND AXIAL PEAKING FACTORS IN THE HEATERS; THE HEATERS WILL BE DESIGNED TO RELEASE HEAT UNIFORMLY OVER THEIR HEATED LENGTH. THE HEAT LOAD AT DESIGN CONDITIONS WILL BE BASED ON BOTH RADIAL AND AXIAL PEAKING FACTORS. THIS WILL IMPOSE A CONDITION MORE SEVERE THAN EXPECTED IN SERVICE.

TO ESTABLISH MAXIMUM FUEL ELEMENT TEMPERATURES, THE TEST DATA WILL BE COMBINED WITH ANALYTICAL CALCULATIONS. THE CALCULATIONS WILL BE BASED ON MAXIMUM OBSERVED BASKET TEMPERATURES IN THE CENTER CAVITY. SINCE THE ANALYTICAL CALCULATIONS OF TEMPERATURE DISTRIBUTION WITHIN THE FUEL ASSEMBLIES MAY BE PERFORMED CONSERVATIVELY AND WITH REASONABLE CERTAINTY, THE TEST PROGRAM WILL NOT INCLUDE MOCK-UP OF FUEL ASSEMBLIES AND MEASUREMENT OF FUEL ELEMENT CLADDING TEMPERATURES.

V MULTIPLICATION TESTS

IT IS RECOMMENDED THAT NEUTRON

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FOOT OF WEST ST. WILMINGTON, DEL.

DRAWING NO.

PAGE 4

MULTIPLICATION TESTS BE PERFORMED AT FIRST LOADING AT EACH REACTOR TO CONFIRM CRITICALITY CALCULATIONS AND ASSURE ADEQUATE SHUT-DOWN MARGIN. SINCE THESE TESTS ARE BEYOND THE SCOPE OF THE CASK DESIGN, FABRICATION AND TESTING CONTRACT, THESE TESTS MUST BE PERFORMED BY REACTOR PLANT PERSONNEL OR OTHER SERVICE ACTIVITY AT THE REACTOR SITE.

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FOOT OF WEST ST. WILMINGTON, DEL.

DRAWING NO.

PAGE 5