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APAE-MEMO-43

REACTORS--POWER

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TEMPERATURE DISTRIBUTION AND THERMAL STRESS IN REACTOR CORE APPR-1

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ILLUSTRATIONS

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In carrying out the study, basic APPR-1 specifications were used where available. Necessary assumptions involving analysis methods, data, and fuel element configuration were made arbitrarily conservative. As a result the computed stress values are indicative of adequate structural design, but do not represent actual expected values.

I - SUMMARY AND CONCLUSIONS

This study was initiated to determine the adequacy of the fuel element structural design of APPR-1. The results obtained lead to the conclusion that the element design is structurally sound for all normal operating conditions from the standpoint of thermal stress.

In carrying out the study, APPR-1 design data was used where available. Necessary assumptions involving methods, data, and configuration were made arbitrarily conservative. As a result the computed stress values are indicative of adequate structural design, but do not represent actual expected values.

Approximate temperature distributions (accurate to 5°F) are shown for fuel plate assemblies with and without assumed surface scale (Figures 2 and 3). Temperature differences between fuel region and brazed joint are 65°F and 100°F for these respective cases.

No thermal stresses in excess of 2500 psi appear to be developed in fuel plates or brazed joints, even when no credit is given for braze penetration in side-plate grooves.

The only significant stresses are the tensile stresses developed in the end plates, which would average about 30,000 psi for the most unfavorable surface scale condition, but which might locally approach 45,000 psi near the junction with the outer fuel plates.

Radiation heating in the core structure would tend to reduce temperature differences; hence relieve thermal stresses.

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II - TEMPERATURE PROFILE THROUGH VERTICAL CROSS SECTION OF FUEL PLATE (See Figure 1)

A - SURFACE WITHOUT SCALE

Temperature datum: Maximum metal temperature: $t_o = 566^oF$ (from APPR-1 design data).

Using maximum q = 4x avg heat-transfer rate,

$$q = 4 \times 55{,}900 = 224{,}000 \frac{Btu}{ft^2 \cdot hr.}$$

Heat generation rate in fuel (maximum):

$$Q = \frac{q}{a} = \frac{224000}{.010/12} = 2.68 \times 10^8 \frac{Btu}{ft^3 \cdot hr.}$$

Δt (ctr to edge of fuel) $= \frac{Qa^2}{2k} = 9.9^oF$

Δt (edge of fuel to surface of plate) $= \frac{qc}{k} = 9.9^oF$

Using datum $t_o = 566^oF$, $t_1 = 556^o$, and $t_s = 546^o$.

Fluid bulk temperature: $t_f = (t_s - q/h) = 546 - \frac{224000}{2570} = 460^oF$.

B -WITH SURFACE SCALE .010" (k = 1.0)

$t_o = 742^oF$ (from design data); $t_1 = 732^o$, and $t_s = 722^o$ (under scale).

Δt through .010" scale with k = 1:

$$\frac{q \times .010}{12 \times 1} = 186^oF$$

$t_s' = 722 - 186 = \underline{536^oF}$ (surface of scale)

Fluid bulk temperature: $536 - \frac{224000}{2570} = \underline{450^oF}$.

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III - DETERMINATION OF TEMPERATURE DISTRIBUTIONS IN HORIZONTAL SECTION NEAR EDGE OF PLATE (Figures 2 and 3)

The isotherms are plotted by comparing thermal resistances of various paths from fuel region to fluid, allowing for variations in effective area. The unfueled portion of the fuel plate is treated as an imperfectly insulated slab, making side-loss corrections about every 10 mils. Intersections of isotherms with plate surface are established by equating ratio of temperature drop within plate to surface-to-fluid temperature difference $(\frac{t_o - t_s}{t_s - t_f})$ to thermal resistance $\frac{\ell}{k}$ of solid path divided by surface resistance 1/h.

Allowance is made for conductivity of braze metal about twice that of steel (21/9.4), but poor mechanical strength and poor thermal contact are assumed in the slots where the fuel plates fit into the side plates. This assumption is probably unnecessarily conservative.

For the surface scale case (Figure 3) a few temperatures, marked outside the boundary, represent the <u>outer surface</u> of the scale, and are of no direct concern in stress determinations. The significant metal temperatures are all marked on the isothermal lines. The scale accounts for $\sim$ 70% of the metal-to-fluid temperature drop at any point.

The temperature distributions appearing in Figures 2 and 3 represent a heat-flux four times average for the core. This occurs only in a short section of the hottest element. Hence temperature differences in most regions will be much smaller than these.

IV - THERMAL STRESS IN INTERIOR FUEL PLATES

Stresses on ℄ of fuel plates are small (Glasstone, Reactor Engineering, pp 709 - 710)*

(Mid-plane)

$$\sigma_o = -\frac{EQa^2}{2k\,(1-\nu)}\left(\frac{c}{a} + \frac{2a^2}{3(a+c)^2}\right) \qquad (11.201.1)$$

$$= -\frac{10^{-5}x3x10^{7}x2.69x10^{8}x10^{-4}}{2.0x9.4x(1-0.3)x144} = -\underline{4010\text{ psi}}$$

(Surface)

$$\sigma_s = \frac{EQa^2}{2k(1-\nu)}\left(1 + \frac{c}{a} - \frac{2a^2}{3(a+c)^2}\right) \qquad (11.201.2)$$

$$= \underline{5110\text{ psi}}$$

Tension at edge of fuel plate, assuming monolithic joint and one direction of restraint; Δ t, ctr to edge, no scale, 65^{o}F (Figure 2).

$$\sigma_e = \frac{\alpha E \Delta T}{1 - \nu} = \frac{10^{-5}x3x10^{7}x6.5}{1-0.3} = 27{,}800\text{ psi}^{**}$$

which ignores yield of braze and elongation of side plate. Corresponding tensile stress for assumed .010" scale (k = 1) is based on Δ t = 100^{o}F (figure 3).

$$\sigma'_e = 27800 \times \frac{100}{65} = 42{,}800\text{ psi}^{**}$$

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*Note exponents missing in text; also Q value in numerical example, p 710, should be $2x10^{8}$. Results in example OK.

**These stresses are later shown to be at least 20-30 times too great, when elongation of side plate is considered.

V - SHEAR ON BRAZED JOINT AND TENSION IN SIDE PLATE

Assume width of braze metal at critical section = .010" on each surface. Let amount of suppressed longitudinal expansion at C of fuel plate = e_1 (inches). Let elongation of side plate = e_2.

Then $e_1 + e_2 = e$ will permit evaluation of S_s and S_t, where e = elongation at fuel plate ℄ resulting from unimpeded thermal expansion with $\Delta t = 65^\circ F$. Consider horizontal plane at mid-length to be fixed reference (see Figure 4).

$$e = \propto L \Delta t = 10^{-5} x 11.5 x 65 = .00747 \text{ inches}$$

Letting S_s = shear stress on braze metal.

$$\mathcal{E} = \text{shear strain} = \frac{e_1}{1.36} = \frac{S_s}{E_s}$$

$$e_1 = \frac{1.36 S_s}{8x10^6} = 1.7x10^{-7} S_s \qquad (1)$$

Assuming shear stress varies linearly along brazed joint from zero at mid-length, the tensile load (lb) on the side plate will be

$$F = \frac{S_s}{2} x 0.02 x 11.5 = 0.115 \; S_s$$

where .02 x 11.5 = effective braze area, 2 sides, half length (assuming braze effective only at corners). Tensile stress in side plate, in terms of its half-length elongation e_2 will be

$$S_t = \frac{F}{0.05x0.164} = 14.0 S_s = \frac{e_2}{11.5} x 3 x 10^7 \qquad (2)$$

where $3x10^7$ = E for steel.

Hence $e_2 = \frac{11.5x14.0}{3x10^7} S_s = 53.6x10^{-7} S_s$ (3)

Adding equations (1) and (3),

$(1.7x10^{-7} + 53.6x10^{-7}) S_s = 55.3x10^{-7} S_s = .00747$ (= e)

$S_s = 1350$ psi (for no-scale case)

$S_s' = 1350 \times \frac{100}{65} = \underline{2080 \text{ psi}}$ with scale

Shear stress on braze is negligible because of elongation of side plate, which develops tensile stress given by equation (2).

$S_t = 14.0x1350 = \underline{18,900 \text{ psi}}$ (no scale)

$S_t' = 14.0x2080 = \underline{29,100 \text{ psi}}$ with scale.

The elongation of the side plate is, from equation (3),

$e_2 = 53.6x10^{-7}x1350 = .00724"$ (no scale)

and the suppressed expansion of the fuel plate (equation 1)

$e_1 = 1.7x10^{-7}x1350 = .00023"$,

which produces an average stress in the fuel plate

$\sigma_e = \frac{e_1}{e} \times 27800 = 855$ psi (no scale)

and

$\sigma_e' = \frac{.00023}{.00747} \times 42800 = 1320$ psi (with scale)

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VI - THERMAL STRESS IN OUTER FUEL PLATES

The outer fuel plates have additional end restraint, and this condition may be approximated by multiplying the σ values in the foregoing section by

$$\frac{1-\nu}{1-2\nu} = \frac{0.7}{0.4} = 1.75, \text{ giving}$$

$$\sigma_e = 1.75 \times 855 = \underline{1500 \text{ psi}} \text{ (no scale)}$$

and

$$\sigma_e' = 1.75 \times 1320 = \underline{2310 \text{ psi}} \text{ (with scale)}$$

The side plates would carry a nearly uniform tensile stress, which might reach 1.5 times the average magnitudes of the foregoing section, in the vicinity of the outer fuel plates (because of less area than average "span").

$$S_t = 1.5 \times 18{,}900 = \underline{28{,}300 \text{ psi}} \text{ (no scale)}$$

$$S_t' = 1.5 \times 29{,}100 = \underline{43{,}600 \text{ psi}} \text{ (with scale)}$$

VII - SYMBOLS AND MAGNITUDES

a = half thickness of fueled region, $\frac{.010}{12}$ ft.

c = thickness of cladding (each side), $\frac{.005}{12}$ ft.

E_s = Shear modulus of braze metal (assumed = 8×10^6 psi)

e_1 = longitudinal strain (suppressed thermal expansion) of fuel plate

e_2 = elongation of side plate (inches)

h = surface conductance = 2570 $\frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F}}$

k = thermal conductivity of SS(304L) = 9.4 $\left(\frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F/ft}}\right)$

Q = Heat generation rate in fuel $\frac{\text{Btu}}{\text{ft}^3 \cdot \text{hr}}$ = 2.68×10^8

q = Heat transfer rate, across fuel plate $\frac{\text{Btu}}{\text{ft}^2 \cdot \text{hr}}$ = 2.24×10^5

S_s = Shear stress on brazed joint

S_t = Tensile stress in side plate

t_o = Maximum center temperature, fueled region of plate =

566°F without surface scale
742°F with .010" scale ($k = 1$)
} from APPR-1 design data

t_1 = temperature at edge of fueled region =

556°F (no scale)

732°F (with scale)

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t_s = Plate surface temperature:

546°F (no scale)

722°F (metal under scale)

536°F (surface of scale)

t_f = Fluid bulk temperature

460°F (no scale)

450°F (with scale)

$\mathcal{E}$ = Unit shear strain in fuel plate = $\frac{e_1}{1.36}$

σ_o = Thermal stress in mid-plane of fuel plate

σ_s = Thermal stress at surface of fuel plate

σ_e = Thermal stress at edge of fuel plate

σ_e' = σ_e for surface scale case

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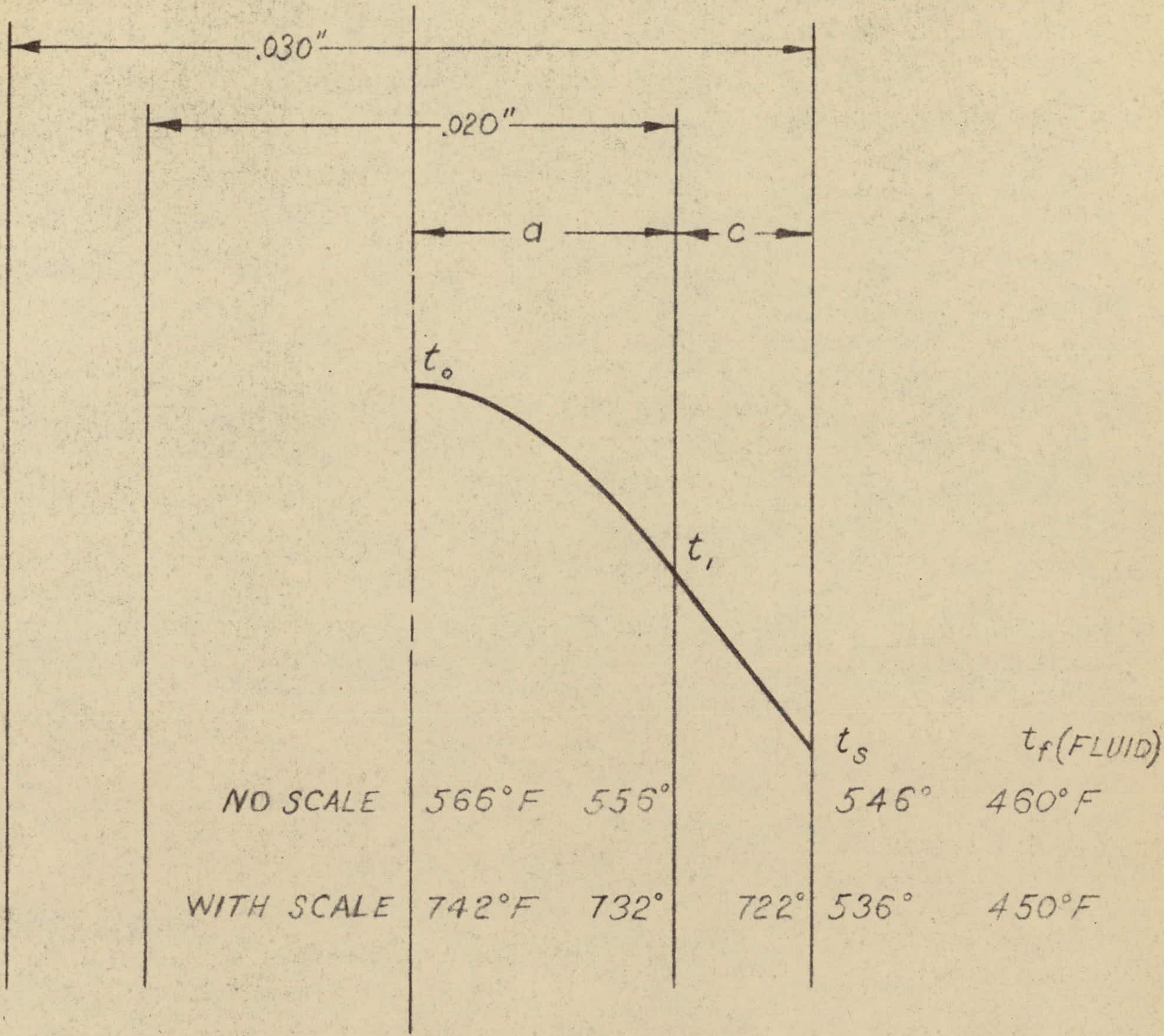

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FIG. 1

TEMPERATURE PROFILE THROUGH FUELED SECTION

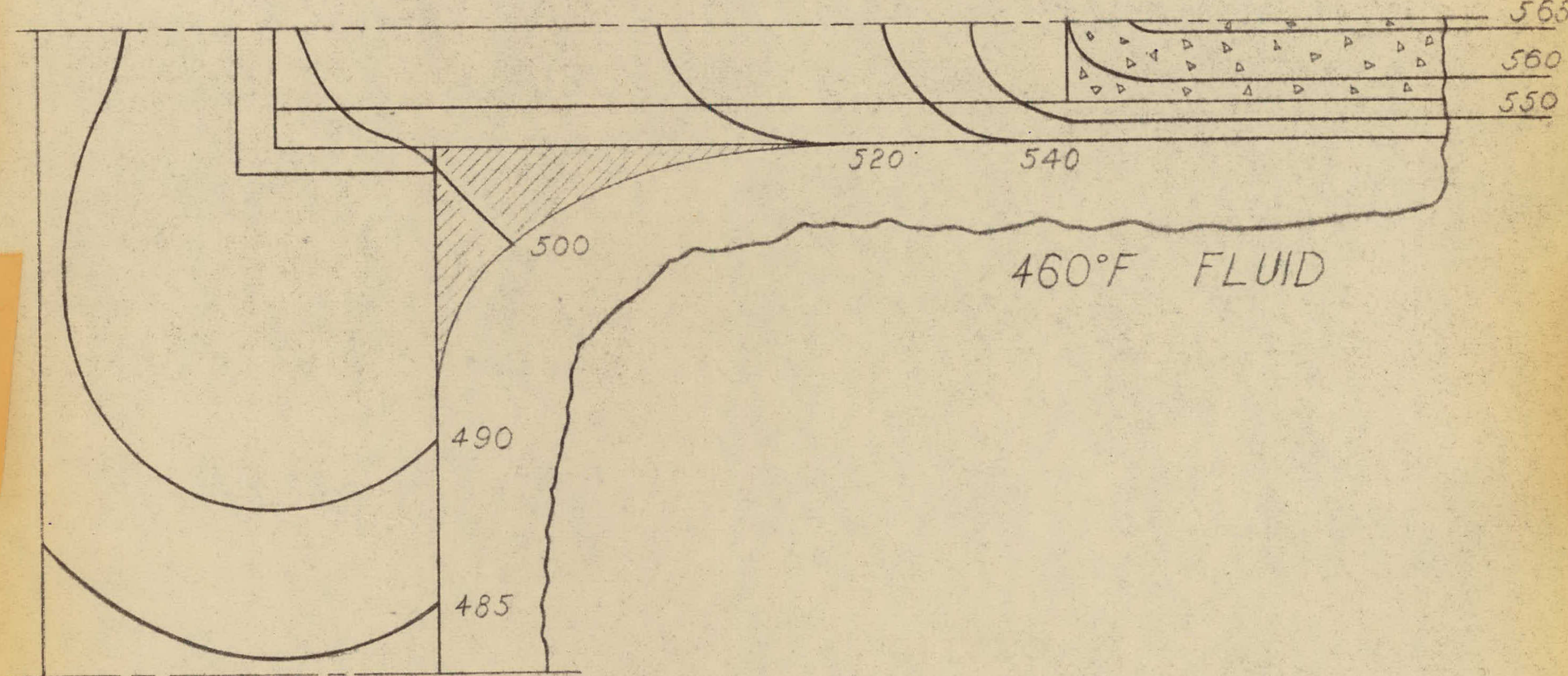

FIG. 2

ISOTHERMS IN FUEL PLATE ASSEMBLY
ASSUMING NO SURFACE SCALE

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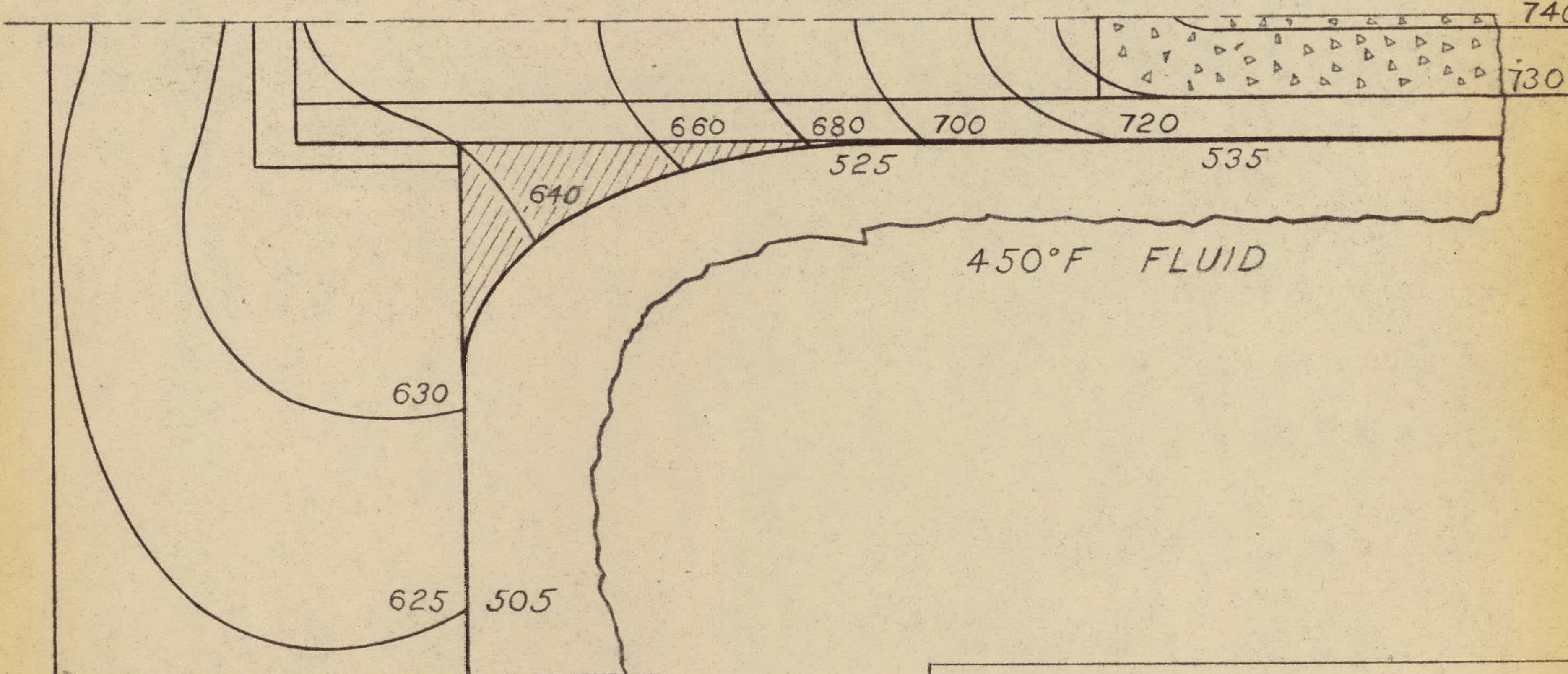

FIG. 3

ISOTHERMS IN FUEL PLATE ASSEMBLY

ASSUMING .010" SCALE WITH k = 1

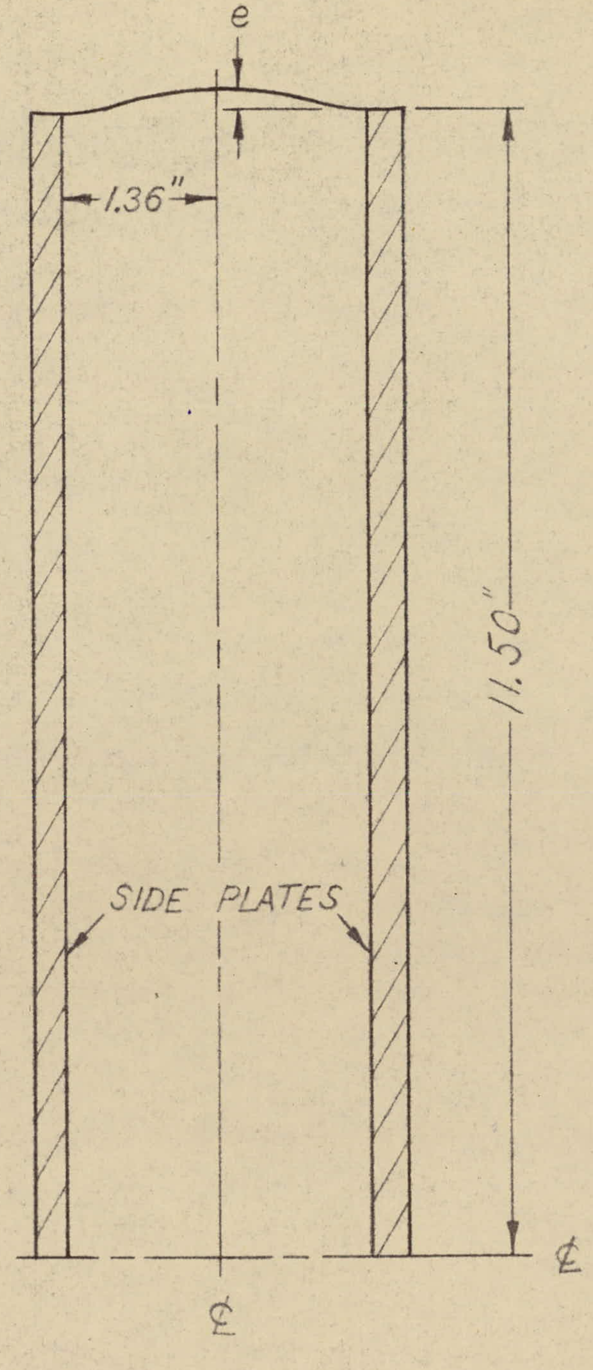

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FIG. 4
THERMAL DISTORTION
OF FUEL PLATE

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