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Date: June 12, 1951

Subject: Thermal Shield and Pressure Shell

Design for 15 Ft. Homogeneous Reactor Tank

at 50 Kw per Liter Specific Power.

To: R. B. Briggs

From: C. L. Segaser

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Abstract

The principal loadings producing stress in the pressure shell and thermal shielding of large homogeneous spherical reactor tanks are due to the internal pressure of the fluid contained and the temperature differentials induced in the shell walls by absorption of leakage radiation from the reactor core. The tangential thermal stress induced by these temperature differentials becomes so large at high reactor power levels that operation may be limited to some lower power unless means are provided to reduce these stresses to tolerable values. A 15 ft. diameter single shell homogeneous spherical reactor is apparently limited to a power level not exceeding 2.5 Kw per liter if the total stress in the pressure shell is not allowed to exceed 15,000 psi as recommended by the 1950 ASME Boiler Code for Unfired Pressure Vessels. The optimum thickness of shell required for such a single shell reactor to contain fluid at 1000 psi pressure is 6 inches at 2.5 Kw per liter.

Two methods are known for reducing the magnitude of thermal stress. The thickness of the shell may be decreased, and/or the shell may be cooled simultaneously on both sides to the same temperature. Either method results in a smaller temperature differential in the wall, and, hence, a lesser thermal stress. Figure 2 of this report shows that a reduction of shell thickness decreases the thermal stress, but the total stress from the combined loading still greatly exceeds the assumed maximum allowable stress of 15,000 psi. To be economically feasible Lane and Briggs have shown that a homogeneous reactor must operate in the order of magnitude of 1,000,000 Kw. At this total power, a 15 ft. diameter reactor must operate at a power density of 20 Kw per liter. At 20 Kw per liter, the optimum pressure shell thickness is approximately 2 inches, but the total minimum tangential shell stress exceeds 40,000 psi.

In order to operate at a power density of 50 Kw per liter, the amount of leakage radiation from the reactor core absorbed by the pressure shell must be reduced to where the total combined stress from pressure and temperature will not exceed the upper allowable design stress for the pressure shell material. It is shown in this report that a total of 6 inches of iron thermal shielding, distributed as shown by Figure 3, is required. With 6 inches of shielding material and cooling space, the inner radius of the necessary pressure shell is 100 inches, which to contain the fluid at 1000 psi pressure, requires a 4-1/2 inch thick steel wall. The maximum stress in the welded joints will, therefore, be not greater than 13,750 psi which will meet the ASME Boiler Code requirement for a welded vessel at joint efficiencies of 90%.

I. Introduction

As emphasized in ORNL-855¹, to be an efficient power producer, a homogeneous type reactor must operate at a relatively high temperature, which in turn implies a correspondingly high pressure if aqueous fuel solutions are employed. The shape of a reactor vessel to satisfactorily contain the solution for maximum utilization of uranium has been shown to be a sphere. It is agreed that the design and construction of a large spherical reactor tank to operate at a pressure of 1000 psi will be difficult and that such fabrication is beyond ordinary engineering practice. However, preliminary contacts with manufacturers of pressure vessels indicate that the fabrication of such a vessel is feasible, but, in general, their recommendations are that the vessel should be limited to the smaller sizes as discussed in ORNL-855, if possible.

The principal limitation to the design and fabrication of such a vessel is the degree to which the shell will be stressed by the forces imposed, and the subsequent selection of a suitably corrosion resistant material having the required physical properties which will withstand the total shell stresses with an adequate factor of safety. The shell of a pressure vessel for homogeneous reactors is subjected to stresses by the following loadings listed in the order of their relative importance:

- (1) Membrane or hoop stresses due to pressure of the contained fluid.
- (2) Thermal stresses in the shell induced by temperature differentials from the heating effect caused by absorption of neutron and gamma leakage radiation from the reactor.
- (3) Localized stresses at nozzle openings into the shell.
- (4) Localized stresses at support points.
- (5) Impact loads, such as ~~rapid~~ pressure rise. (May occur due to gas explosions.).
- (6) Weight of the vessel and contents, including ~~super-imposed~~ loads supported by the shell.
- (7) Additional pressure due to static head of the solution.

The maximum direct stress, determined by any combination of these loadings that are expected to occur simultaneously during normal operation of the reactor, shall not exceed an arbitrarily selected allowable working stress of 15,000 psi, corresponding to a minimum tensile strength of 60,000 psi as given for one of the materials listed in Table UG-23 of the 1950 ASME Boiler Construction Code for Unfired Pressure Vessels². The temperature of the metal shall not be allowed to exceed 650°F.

According to UG-27 of the 1950 ASME Code for Unfired Pressure Vessels, the thickness of the shell of a wholly spherical vessel may be computed by the formula,

$$t = \frac{PR}{2 SE - 0.2 P}$$

where,

- t = Minimum required thickness of shell plates, inches (exclusive of corrosion allowance).
- P = Design pressure, psi.
- R = Inside radius of the shell course, inches (before corrosion allowance is added).
- S = Maximum allowable working stress, psi.
- E = Efficiency of joints.

It is assumed that fabrication shall follow the rules for fusion welded construction as described in Part UW of the 1950 ASME Code, wherever possible. Since the outer pressure shell exceeds 1.250 inches, the type of joint is assumed to be a double-welded butt joint. For a double-welded butt joint or circumferential single-welded butt joint with backing strip, radiographed but not stress-relieved, a joint efficiency of 90% is allowed. The thickness of plate required, exclusive of corrosion allowance, is, therefore 3.360 inches strictly to withstand the internal pressure loading alone, for a single-shell reactor vessel of 15 ft. inside diameter at 1000 psi pressure.

However, it may be shown that even for low reactor power levels the temperature rise in the metal from absorption of gamma and neutron leakage radiation will produce very large thermal stresses in the shell which, when added to the hoop-stress from pressure may result in excessive total tangential stresses. The tangential thermal stress is shown to be directly proportional to the wall thickness and also to the power level, increasing as the thickness and power are increased. On the other hand, the hoop-stress from pressure decreases as the wall thickness is increased. The resulting total stress curve will, when plotted as a function of thickness, produce a concave curve, the minimum point of which will correspond to the optimum wall thickness.

It is the purpose of this report to determine the optimum wall thickness and maximum power level of operation of a 15 ft. inside diameter homogeneous spherical reactor vessel, and to specify the required amount of thermal shielding to make operation at high power levels feasible.

II. Radiation Spectrum Data

From the following data, furnished by R. B. Briggs for a 15 ft. diameter critical mass of uranium - heavy water solution, the neutron and gamma currents into the shell of the reactor tank were calculated.

Fraction of fast neutrons leaking per fission	0.095
Fraction of thermal neutrons leaking per fission	0.174
Number of 6 Mev. Sulfur capture gammas per fission	0.120
Number of 6 Mev. Uranium capture gammas per fission	1.112
Number of 1 Mev. prompt gammas per fission	5.000
Number of 2.5 Mev. fission product gammas per fission	2.000
Ratio of heavy water atoms to uranium atoms	80.000

III. Neutron and Gamma Currents Into Shell

Volume of 15 ft. spherical tank (liters)	5×10^4
Specific power of reactor (kw per liter)	50
Total power of reactor (kw)	2.5×10^6
Total fissions per second at 3.1×10^{13} sec ⁻¹ per kw	7.75×10^{19}
Inside surface area of tank (cm ²)	6.57×10^5
Total fast neutrons leaking into tank (sec ⁻¹)	7.35×10^{18}
Total thermal neutrons leaking into tank (sec ⁻¹)	1.35×10^{19}
Total 6 Mev. capture gammas generated in tank (sec ⁻¹)	9.55×10^{19}
Total 1 Mev. prompt gammas generated in tank (sec ⁻¹)	3.88×10^{20}
Total 2.5 Mev. fission product gammas generated (sec ⁻¹)	1.55×10^{20}

(A) Fast Neutron Current Into Tank Wall

$$J_f = \frac{7.35 \times 10^{18}}{6.57 \times 10^5} \text{ (neutrons per cm}^2 \text{ - sec.)} \quad 1.12 \times 10^{13}$$

(B) Thermal Neutron Current Into Tank Wall

$$J_s = \frac{1.35 \times 10^{19}}{6.57 \times 10^5} \text{ (neutrons per cm}^2 \text{ - sec.)} \quad 2.06 \times 10^{13}$$

(C) Gamma Current Input Into Tank Wall

The probability that a gamma photon will escape on first flight from a homogeneous sphere has been calculated by Castle, Ibser, Sacher and Weinberg and the results abstracted in tabular form in TNX-7 (Computation of Radiation Hazards)³. This data has been recalculated to extended values of the product of the absorption coefficient of the emitter and its radius and the results plotted in Figure 1. Using the probability data from this curve, the following gamma currents into the shell of the reactor are determined.

	(30 ft.)	(15 ft.)
1. <u>Gamma Flux into shell resulting from</u>		
<u>6 Mev. capture γ's generated by sulfur:</u>		
Number γ 's generated in sphere (sec ⁻¹)	1.17×10^{20}	9.3×10^{18}
Ratio of D ₂ O to U. (β)	140	80
Absorption coefficient for 6 Mev. γ 's (cm ⁻¹)	0.031	0.0335
Radius of sphere (cm)	458	229
Product (μR)	14.2	7.67
Fraction total γ 's leaking into sphere shell	0.07	0.12
Number γ 's leaking into shell (sec ⁻¹)	8.2×10^{18}	1.12×10^{18}
Total γ energy into shell (Mev. - sec ⁻¹)	4.92×10^{19}	6.72×10^{18}
Inside area of shell (cm ²)	2.62×10^6	6.57×10^5
Energy flux into shell (Mev./cm ² -sec.)	1.88×10^{13}	1.02×10^{13}

(30 ft.)

(15 ft.)

2. Gamma flux into shell resulting from
6 Mev. capture γ 's in Uranium

Number γ 's generated in reactor per sec.	7.38×10^{20}	8.63×10^{19}
Absorption coefficient (cm ⁻¹)	0.031	0.0335
Product (μ R)	14.2	7.67
Fraction γ 's leaking into shell/sec.	0.07	0.12
Number γ 's leaking into shell per sec.	5.17×10^{19}	1.04×10^{19}
γ energy into shell (Mev/sec)	3.1×10^{20}	6.24×10^{19}
γ energy current into shell (Mev/cm ² -sec)	1.18×10^{14}	9.5×10^{13}

3. Gamma flux into shell resulting from
1 Mev. prompt γ 's

Number γ 's generated in reactor per sec.	3.1×10^{21}	3.87×10^{20}
Absorption coefficient (cm ⁻¹)	0.067	0.072
Product (μ R)	30.7	16.5
Fraction of γ 's leaking into shell/sec.	0.0328	0.060
Number γ 's leaking into shell per sec.	1.01×10^{20}	2.32×10^{19}
γ energy into shell (Mev/sec.)	1.01×10^{20}	2.32×10^{19}
γ energy current into shell (Mev/sec-cm ²)	3.86×10^{13}	3.54×10^{13}

4. Gamma flux into shell resulting from
2.5 Mev. fission - product γ 's

Number γ 's generated in reactor per sec.	1.24×10^{21}	1.55×10^{20}
Absorption coefficient (cm ⁻¹)	0.0415	0.0435
Product (μ R)	19	9.96
Fraction of γ 's leaking into shell	0.05	0.10
Number γ 's leaking into shell per sec.	6.2×10^{19}	1.55×10^{19}
γ energy into shell (Mev/sec.)	1.55×10^{20}	3.87×10^{19}
γ energy current into shell (Mev/cm ² -sec)	5.92×10^{13}	5.90×10^{13}

Summarized, the following radiation currents into the shell of a 15 ft. diameter homogeneous spherical reactor at 50 kw per liter specific power have, therefore, been used to determine the heat production in the iron.

Fast neutron current into shell	1.12×10^{13} neuts/cm ² -sec.
Thermal neutron current into shell	2.06×10^{13} neuts/cm ² -sec.
6 Mev. gamma current into shell	1.75×10^{13} photons/cm ² -sec.
2.5 Mev. gamma current into shell	2.36×10^{13} photons/cm ² -sec.
1 Mev. gamma current into shell	3.54×10^{13} photons/cm ² -sec.

IV. Heat Production in Iron Shells

The method of computing heat production per unit volume in a thermal shield and pressure vessel, as reported by Grotenhuis in ANL-4379⁴, has been essentially adopted for these calculations. Since the radius of the shell is large, little error is introduced by assuming infinite slab geometry. With this assumption and using diffusion theory, the calculations are much simplified.

In general, the method consists of determining the neutron or gamma flux at a distance into the shell, multiplying this by the linear absorption coefficient or the macroscopic cross-section which gives the collision density, and knowing the energy release per collision, the energy produced per unit volume at the point is determined. Admittedly, these assumptions lead to an overestimate of energy release since all energy is assumed to be given off at the point of collision. These assumptions are not believed to produce appreciable error insofar as primary gamma absorption from the reactor is concerned. However, when a neutron is absorbed by the iron a 7 Mev. gamma is produced. Obviously, this energy cannot be rigorously assumed to be absorbed where the capture occurs, but must be absorbed in space around the position where the neutron was captured. In a finite shell or slab thickness some of these gammas escape and hence do not contribute to the heating of the shell. The primary gamma current and the neutron currents entering the shell are about equal in magnitude, hence, calculations based on this method should not be high by more than a factor of two and probably closer to 1.5. For engineering purposes, such results should certainly give conservative answers for a first approximation of required thermal shielding and pressure shell thickness. Using nuclear data from the literature for pure iron, this method results in the following equation for total heat generation in the steel thermal shield and pressure shell of a 15 ft. inside diameter spherical reactor tank at 50 Kw per liter.

$$H_T = 3.91 \times 10^5 e^{-7.33 x} + 2.72 \times 10^5 e^{-9.0 x} + 2.54 \times 10^5 e^{-14.2 x} \\ + 1.69 \times 10^6 e^{-22.9 x} + 6.1 \times 10^3 e^{-1.31 x} + 8.84 \times 10^3 e^{-5.6 x}$$

where,

$$H_T = \text{Total heat generation, Btu/ft}^3 \text{ - hr.} \\ x = \text{Distance into shell, ft.}$$

V. Temperature Distribution Through Shells⁶

Since the thermal stress induced in the shell is a function of the temperature distribution, the first step involved in computing these stresses is the determination of the temperatures thru the shell slabs. As in the case of heat generation, infinite flat slab geometry is assumed. The variation of the properties of the metal with temperature is neglected, average values being assumed for the calculations. The differential equation for heat conduction in an infinite flat slab with internal heat production is:

$$\frac{d^2t}{dx^2} = - \frac{W}{K}$$

As shown in Section IV, the heat generation in the metal is an exponential equation of the general form: -

$$W = A e^{-\alpha x}$$

Substituting in the differential equation of heat flow:

$$\frac{d^2 t}{dx^2} = - \frac{A e^{-\alpha x}}{K}$$

The solution of this equation is obtained by two successive integrations from which the temperature gradient is:

$$\frac{dt}{dx} = \frac{A}{\alpha K} e^{-\alpha x} + C_1$$

and the temperature distribution is:

$$t = - \frac{A}{\alpha^2 K} e^{-\alpha x} + C_1 x + C_2$$

The determination of the constants C_1 and C_2 depends upon the assumed boundary conditions. One may imagine the reactor to be operated (1) with the outside surface fully insulated in which case the gradient will be zero at $x = T$ and all of the heat generated will flow into the fuel solution, (2) with the outside surface of the reactor cooled to substantially the ambient air temperature, or (3) the outside surface cooled to the same temperature as the inside surface. Case 2, will subsequently be neglected since obviously such operation will result in the greatest temperature differentials and hence the largest thermal stresses.

where,

- t = Temperature, $^{\circ}\text{F}$
- A = Coefficient in heat generation term
- α = Exponent in heat generation term
- K = Thermal conductivity, $\text{Btu/hr-ft}^2 - ^{\circ}\text{F/ft.}$
- T = Thickness of slab, ft.
- x = Distance into slab from inner surface, ft.

VI. Thermal Stress in Hollow Spheres⁷

The state of stress in hollow spheres subject to temperature differentials has been studied by Timoshenko and others. Timoshenko⁸ has shown that the radial and tangential stresses in the shell of a hollow sphere may be calculated from the following equations:

$$\sigma_r = \frac{2 \alpha E}{1 - \nu} \left[\frac{r^3 - a^3}{(b^3 - a^3)r^3} \int_a^b T r^2 dr - \frac{1}{r^3} \int_a^r T r^2 dr \right]$$

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however, shown to be operable at power densities up to 50 kw per liter. With this system, radiation from the core is absorbed by the inner shells with the result that radiation entering the outer shell is reduced to the point where the total shell stress developed is less than 15,000 psi. This system and the calculations based upon it, implies that each of shells 2, 3, and 4 are integrally welded. Actually, if the reactor fuel solution is used for coolant, the pressure on each surface of the shell is equalized and it is not mandatory that these shells be fully welded. They may consist of segments of spherical surfaces mechanically held in position relative to the outer pressure shell. The outer pressure shell with this system must be designed to resist the full 1000 psi internal pressure plus the residual thermal stresses induced by radiation.

It has also been suggested that if a system of individual pressures between shells is adapted, that the outer pressure shell may possibly be eliminated. In other words, Table 6 shows that after deduction of the induced thermal stress from radiation, each shell is capable of sustaining a certain differential pressure without exceeding a total stress of 15,000 psi. For instance, shell no. 1 can sustain a maximum internal pressure differential of 150 psi. Therefore, the pressure in the space between Shells 1 and 2 can be as little as 850 psi. Shell 2 is capable of holding 315 psi, therefore the space between shells 2 and 3 can be maintained at 535 psi. Shell No. 3 can sustain 473 psi, making the pressure in the space between Shells 3 and 4 equal to 62 psi. However, shell no. 4 is capable of holding the fluid at 627 psi or an excess of 565 psi. Instead of pressurizing each space, therefore, the space between Shells 1 and 2 and between Shells 2 and 3 can be held at the core pressure of 1000 psi. With shell 3 being capable of taking a 473 psi pressure differential, the space between shells 3 and 4 could be held at 527 psi. This pressure can be safely sustained by shell 4 which is capable of holding 627 psi. However, these pressure differentials were calculated on the assumption of equal temperature on either face of each shell. Hence, the outer surface of Shell no. 4 would have to be cooled equal to the inner surface if this system was adapted and shell no. 5 eliminated.

FIGURE 1

GAMMA LEAKAGE FROM HOMOGENEOUS SPHERICAL REACTOR

Radiation at surface of homogeneous sphere
without self-absorption -----

$$2\pi I_0 R$$

Radiation at surface of homogeneous sphere
with self-absorption -----

$$\frac{\pi I_0}{\mu^2 R} [2\mu R + e^{-2\mu R} - 1]$$

Fraction of radiation escaping -----

$$\frac{2\mu R + e^{-2\mu R} - 1}{2(\mu R)^2}$$

Where: μ = Absorption coefficient of emitter - Cm.^{-1}
 R = Radius of sphere - Cm.

FIGURE 2

OPTIMUM WALL THICKNESS AND MAXIMUM ALLOWABLE SPECIFIC POWER OF OPERATION FOR SINGLE SHELL 15 FT. INSIDE DIAMETER SPHERICAL HOMOGENEOUS REACTOR TANK

FIGURE 3

HEAT GENERATION THROUGH THERMAL SHIELD AND PRESSURE SHELL OF 15 FT. INSIDE DIAMETER
SPHERICAL HOMOGENEOUS REACTOR TANK AT 50 KILOWATTS PER LITER SPECIFIC POWER

Total Heat Generation
Gamma Heat Generation
Thermal Neutron Heat Generation
Fast Neutron Heat Generation

—————

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FIGURE 4

TEMPERATURE DISTRIBUTION THROUGH THERMAL SHIELD AND PRESSURE SHELL OF 15 FT. INSIDE DIAMETER REACTOR TANK

Drawing # 11554

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FIGURE 5

REQUIRED WALL THICKNESS OF PRESSURE SHELL FOR 15 FT. DIAMETER SPHERICAL HOMOGENEOUS REACTOR AT 50 KW. PER LITER SPECIFIC POWER FOR THERMAL SHIELD THICKNESSES OF 4, 5, AND 6 INCHES.

TANGENTIAL SHELL STRESS - PSI

FIGURE 6

TEMPERATURE AND TANGENTIAL STRESS DISTRIBUTION IN CORE-TANK OF 15 FT. INSIDE DIAMETER HOMOGENEOUS SPHERICAL REACTOR TANK AT 50 KILOWATTS PER LITER SPECIFIC POWER

FIGURE 7

TEMPERATURE AND TANGENTIAL STRESS DISTRIBUTION IN PRESSURE SHELL OF 15 FT. INSIDE DIAMETER HOMOGENEOUS SPHERICAL REACTOR TANK AT 50 KW. PER LITER SPECIFIC POWER

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1. Homogeneous Reactors -- Stress
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FOR NSA USE:

Homogeneous reactors -- thermal shields and pressure shell designs of 15-ft

Pressure vessels -- design for 12-ft homogeneous reactor tank

Thermal radiation shielding -- design for 15-ft homogeneous reactor

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