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OAK RIDGE NATIONAL LABORATORY

Operated By

CARBIDE AND CARBON CHEMICALS COMPANY

POST OFFICE BOX P
OAK RIDGE, TENNESSEE

**ORNL
CENTRAL FILES NUMBER**

CF-52-10-81

DATE: October 9, 1952

SUBJECT: Thermal Stress in the ISHR Pressure Vessel

TO: File

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CLASSIFICATION CANCELLED
DATE 12-19-55
For The Atomic Energy Commission
H. F. Dancy
Chief, Declassification Branch

Classification cancelled (or changed to) CONFIDENTIAL
by authority of AEC Form 381
by Ernestine Johnson TISOR, date 11/10/55

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Introduction

The present conception of a single core ISHR includes a laminated steel thermal shield between the stainless core tank and the outer steel pressure vessel. According to R. H. Chapman, for a 6 ft. inside diameter reactor operating at 15 kw/liter, 250°C and 1000 psi. pressure, 2 to 3 inches of thermal shield is required. Two inches of shielding allows a total stress of 10,000 psi. in a 2.75" thick pressure vessel; 3" of shielding gives the same stress in a 2.25" wall. At 75 kw/liter, the stresses are 22,000 psi. and 16,000 psi., respectively.

It is believed that substantial simplifications in construction of the ISHR, and more flexibility of power operation can be effected by the following methods:

1. Substitution of borated water thermal shielding for the present steel.
2. Controlled cooling of the outside surface of the pressure vessel.

It is the purpose of this memorandum to illustrate the effectiveness of these procedures. The calculations which are presented are approximate in nature, so that additional time-consuming refinements would be needed to optimize the design of a thermal shield under the new basis.

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Reactor Model

The model which is under consideration is the following:

Reactor diameter	6 ft. I.D.
Power level	15 kw/liter
Temperature	250 °C
Pressure	1000 psi.
Thickness of inner core tank (stainless steel)	1.905 cm. (3/4")
Thickness of borated water thermal shielding	11.5 cm. (4.53")
Temperature of thermal shield	250 °C
Pressure of thermal shield	1000 psi.
Thickness of pressure shell (carbon steel)	8 cm. (3.15")
Outside diameter of pressure vessel	7.4 ft.
Neutron current into core tank, thermal*	$2.1 \times 10^{12}/\text{cm}^2 \text{ sec.}$
fast	$1.92 \times 10^{12}/\text{cm}^2 \text{ sec.}$
Gamma Current into core tank, 6 Mev**	$8.16 \times 10^{11}/\text{cm}^2 \text{ sec.}$
2.5 Mev	$5.41 \times 10^{12}/\text{cm}^2 \text{ sec.}$
1 Mev	$3.57 \times 10^{12}/\text{cm}^2 \text{ sec.}$

* Haubenreich

** Chapman

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~~CONFIDENTIAL~~Physical and Nuclear Properties

The following physical properties of steel and water at 250°C were assumed:

Carbon steel, modulus of elasticity, E	30 x 10 ⁶ psi.
coefficient of thermal expansion, α	6.7 x 10 ⁻⁶ /°F.
thermal conductivity, k	1.5 x 10 ¹² Mev/sec.cm.°F
Poisson's ratio, ν	0.3
density	7.98 g./c.c.
H ₂ O, density	0.8 g./c.c.

The following nuclear properties of stainless steel at 250°C were assumed*:

macroscopic absorption cross-section, Σ_a	0.183/cm.
diffusion coefficient of thermal neutron, D	0.324 cm.
inverse diffusion length, thermal, λ	0.752/cm.

The following gamma cross-sections, μ , were assumed for steel and water at 250°C, after correction for multiple scattering by dividing the true cross-sections by 1.2:

Gamma Energy, Mev	for steel, cm ⁻¹	for water, cm ⁻¹
7	0.201	0.0168
6	0.205	0.0181
2.5	0.246	0.0292
1	0.390	0.0471

CalculationsI. Gamma Source in Stainless Steel Core Tank

The thermal neutron current into the core tank, $2.1 \times 10^{12}/\text{cm}^2 \text{ sec.}$, results in the production of 7 Mev gammas from neutron absorption in stainless steel. Considering slab geometry for the thin tank, and also

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assuming the borated water black to neutrons, the flux distribution in the stainless steel can be expressed:

$$\phi = a \sinh \lambda x \quad (1)$$

where ϕ is thermal flux, neut/sec.cm.²

a is a constant

x is thickness, cm.

λ is inverse diffusion length, cm.⁻¹

Differentiating equation (1), and multiplying by D , (diffusion coefficient in stainless steel):

$$D \frac{d\phi}{dx} = D \lambda a \cosh \lambda x = \text{leakage current} \quad (2)$$

Assuming an extrapolation distance on the borated water side of $2.31 D$, or 0.69 cm., the flux can be expressed by solving equation (2) for a .

$$\phi = 2.4 \times 10^{12} \sinh 0.752 x \quad (3)$$

where x is thickness measured from the extrapolation distance. The corresponding gamma production, $\Sigma_a \phi$, is:

$$\Sigma_a \phi = 4.39 \times 10^{11} \sinh 0.752 x \text{ } \gamma\text{'s/cm}^3\text{sec.} \quad (4)$$

Integrated gamma production in the stainless steel is 1.43×10^{12} /cm²sec.

A simplifying assumption is now made, that the gammas all originate at the midpoint of the tank wall and half of them fly out toward the borated water. This assumption is basically pessimistic because the average gamma is produced closer to the reactor than the midpoint of the core tank wall. After correcting for absorption in stainless steel, the 7 Mev gamma current into the borated water is 5.9×10^{11} /cm²sec.

II. Gamma Current into the Pressure Vessel

Gamma leakage from the reactor must pass through 1.905 cm. of stainless steel and 11.5 cm. of water before the gammas enter the pressure vessel. An additional attenuation is caused by the increase in area as gammas travel outward in spherical geometry. Expressed mathematically:

$$J_1 = J_0 e^{\mu_{Fe} x_{Fe}} e^{\mu_{H_2O} x_{H_2O}} \frac{A_0}{A_1} \quad (5)$$

J is gamma current, in gammas/cm²sec.

x is thickness, cm.

μ is gamma cross-section, cm⁻¹

A is area, cm²

Subscripts 0, 1 refer to inner wall of core tank and inner wall of pressure shell, respectively.

The gamma currents computed by equation (5) are:

<u>Gamma Energy</u> <u>Mev</u>	<u>Current, J₁</u> <u>per cm² sec.</u>	<u>Energy Current at Pressure</u> <u>Shell, J₁' Mev./cm²sec.</u>
7	3.63 x 10 ¹¹	2.54 x 10 ¹²
6	3.33 x 10 ¹¹	2.00 x 10 ¹²
2.5	1.80 x 10 ¹²	4.50 x 10 ¹²
1	7.37 x 10 ¹¹	7.37 x 10 ¹¹

III. Neutron Leakage into the Pressure Vessel

It is assumed that boron will reduce the thermal flux to a negligible level. The fast flux will also be attenuated to some extent in the H₂O.

Thermal stress caused by fast neutrons has been found to be small by Chapman, and it is neglected here.

IV. Thermal Stress in the Pressure Shell

The heating source for gammas of a particular energy is:

$$\frac{\text{Mev}}{\text{cm}^3} = \mu J_1' e^{-\mu x} \quad (6)$$

where x is distance from inner face of pressure vessel, cm.

For convenience, the total heating at all energies is denoted by

$$\sum \mu J_1' e^{-\mu x}.$$

The source term is equated to the heat leakage in slab geometry:

$$\sum \mu J_1' e^{-\mu x} = -k \frac{d^2 T}{dx^2} \quad (7)$$

where T is temperature in $^{\circ}\text{F}$. and k thermal conductivity in $\text{Mev.}/\text{sec.cm.}^{\circ}\text{F}$.

Integrating equation (7),

$$\sum J_1' e^{-\mu x} + C_1 = k \frac{dT}{dx} \quad (8)$$

$$\sum \frac{J_1'}{\mu} e^{-\mu x} + C_1 x + C_2 = kT \quad (9)$$

Integrating equation (9) to solve for average temperature in the shell,

$$XkT_{\text{av}} = \int_0^X \left(\sum \frac{J_1'}{\mu} e^{-\mu x} + C_1 x + C_2 \right) dx = \sum \frac{J_1'}{\mu^2} (e^{-\mu X} - 1) + \frac{C_1 X^2}{2} + C_2 X \quad (10)$$

where X is total thickness of the pressure shell, cm.

C_1 and C_2 are constants depending on boundary conditions.

T_{av} is the average temperature of the shell, $^{\circ}\text{F}$.

The maximum thermal tensile stress occurs at the minimum temperature. The stress, in slab geometry, is:

$$\sigma = \frac{\alpha E}{1 - \nu} (T_{av} - T) \quad (11)$$

where σ is thermal stress, psi.

α is coefficient of thermal expansion, $^{\circ}\text{F}^{-1}$

E is elastic modulus, psi.

ν is Poisson's ratio

IV A. Thermal Stress, Outside Insulated

For the case of thermal insulation on the outside of the pressure shell, the boundary conditions on equation (8) and (9) are:

$$k \frac{dT}{dx} = 0 \quad \text{when } x = X = 8 \text{ cm.} \quad (12)$$

$$T = 0 \text{ at } x = 0 \text{ (datum temperature)} \quad (13)$$

Substituting the boundary conditions, the gamma energy currents of section II, and the gamma cross-sections into equations (8) and (9),

$C_1 = -1.555 \times 10^{12}$ and $C_2 = 4.26 \times 10^{13}$. From equation (10), $T_{av} = 11.14$ $^{\circ}\text{F}$ and from equation (11), the thermal stress is 3,200 psi. at the inside edge of the pressure shell, where $T = 0$. This stress is proportional to power level of the reactor.

IV B. Thermal Stress, Outside Wall Cooled to Temperature of Inside Wall

In this case, the boundary conditions are:

$$T = 0 \text{ at } x = 0; \quad T = 0 \text{ at } x = 8 \quad (14)$$

Substituting both boundary conditions into equation (9), $C_1 = -4.44 \times 10^{12}$ and $C_2 = 4.26 \times 10^{13}$. $T_{av} = 3.44$ $^{\circ}\text{F}$. and thermal stress at the inside wall is 990 psi.

V. Pressure Stress in Pressure Shell

The thin sphere formula,

$$\sigma = \frac{pr}{2X} \quad (15)$$

where p = internal pressure, psi.

r = inside radius of sphere, cm.

X = sphere thickness, cm.

is used to predict a pressure stress of 6560 psi.

Results and Conclusions

The table below lists the total stress as a function of the power density for the two systems considered.

Power Density kw/liter	Total Stress, psi.	
	<u>Outside Insulated</u>	<u>Outside Cooled</u>
15	9,760	7,550
30	12,960	8,540
45	16,160	9,530
60	19,360	10,520
75	22,560	11,510

The results indicate that borated water can serve as thermal shielding.

The advantages of boron over the present steel shielding are:

1. The mechanical complications of the laminated steel thermal shield are eliminated, although there remains the complication of an inner stainless core tank and an outer pressure shell.
2. Induced activity in the steel pressure shell would be cut down considerably by reducing the thermal flux.

3. The shielding requirements for the reactor might be lowered somewhat by the reduced sources of thermal neutrons and 7 Mev gammas.

It is likely that a soluble boron compound which is noncorrosive can be found. Borates are sometimes used as corrosion inhibitors in steam plants.

The results show that cooling of the outside wall is extremely effective in reducing thermal stress. This has application to any design for thermal shielding.

Cooling of the outside wall can be accomplished with cooling coils circulating borated water, or with air circulation.

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