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Post Office Box X
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ORNL
CENTRAL FILES NUMBER

59-2-78

Internal Security - Atomic Energy

COPY NO. 102

DATE: February 25, 1959

SUBJECT: Analysis of Neutron Pulses in a Godiva-Type Reactor

TO: Distribution

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SUMMARY

Some calculations have been made to estimate the characteristics of a neutron-burst type fast reactor similar to Godiva but made up of relatively small component parts - the so-called "layered assembly." One spherical and three cylindrical assemblies have been considered. Critical masses, assuming 5% voids, range from 58 to 65 kg of 93.4% enriched U^{235} . For a reactivity addition of 0.33 dollars above prompt critical, bursts between 2×10^{17} and 6.7×10^{17} fissions were computed with accompanying temperature rises varying from 514 to 1600°C. The burst width at half-maximum was about 12 microseconds. To obtain an idea of the possibilities of stress reduction which might be achieved by layering, an assembly made of small rings was considered.

While the critical masses obtained here are believed to be fairly accurate, the predictions concerning mechanical energy generated, total fissions, and burst width may be subject to sizeable error due to the many simplifications required to allow hand computations. Nevertheless, considerable improvement in safety and burst-size is indicated by the use of a "layered assembly" instead of an assembly composed of relatively thick parts.

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ANALYSIS OF NEUTRON PULSES IN A GODIVA-TYPE REACTOR

C. W. Nestor and Melvin Tobias

I. INTRODUCTION

The calculations described in this report represent an attempt to determine the characteristics of a neutron-burst reactor similar to Godiva but embodying improvements suggested by experience with that assembly. These improvements are intended to provide additional safety in operation as well as to enable possible operation at considerably higher burst levels. Godiva-II is composed of three solid blocks of 93.5% enriched uranium, a large safety block, two shim rods, and a burst rod. Its performance is limited to the 10^{16} fission level by the stresses, mechanical energy, and temperatures which may be developed in a burst. The temperature limitation may perhaps be relaxed by the use of a uranium-molybdenum-zirconium alloy (yet to be completely developed). Such an alloy is believed to be stronger at high temperatures than ordinary uranium and is also said to be free of the anisotropic growth phenomena observed in the latter.¹ To alleviate the large stresses occasioned by the use of thick component pieces, the structure of the reactor should be degraded into what Stratton² and his co-workers at Los Alamos refer to as a "layered" assembly. By this is meant a more or less loose assembly made up of rods, concentric cylinders, or the like, in which the individual pieces are generally free to expand relatively independently of one another as the burst energy is released. The inertial effects which lead to the development of large internal stresses and the generation of considerable amounts of mechanical energy may be considerably reduced.

This report is concerned with a description of the bursts which might be obtainable from layered assemblies employing a 19% Mo uranium-molybdenum alloy following a reactivity addition of 1% over delayed critical. Total fissions, the burst width at half maximum, critical masses, and temperature rises have been computed for three cylindrical reactors and a spherical reactor using a one-group diffusion model and neglecting inertial and stress effects. For simplicity, it was assumed that the nuclear properties are affected in a uniform manner by the heat generation. To evaluate how much the inertial effects might enhance the burst, an assembly made of 1-inch diameter rings of negligible thickness was considered, again assuming that the heat generation effect was uniform. Because of the mathematical complexities involved, no evaluation of bursts in a cylindrical reactor composed of rods or shells can be made at this time, although it is possible to perform the analysis by numerical methods which would not require the use of the simplifications made here.

II. COMPUTATION OF CRITICAL SIZE

A. Method

Critical dimensions of spheres and cylinders were calculated using the modified one-group diffusion theory approach described by Codd, Shepherd and Tait.³

For a given material the critical geometric buckling B is the solution of the transcendental equation

$$\frac{B}{\alpha} = \tan \frac{B}{\beta} \quad (1)$$

where $\alpha \equiv \Sigma_t$

$\beta \equiv \nu \Sigma_f + \Sigma_s$ (See Table IV for definition of symbols)

For a sphere the critical extrapolated radius $\tilde{R}$ is given by

$$\tilde{R} = \frac{\pi}{B} \quad (2)$$

and the actual critical radius R_c is given by

$$R_c = \tilde{R} - \frac{0.71}{\beta} \quad (3)$$

For a cylinder the critical extrapolated radius is given by

$$\tilde{R} = \frac{C}{B} \quad (4)$$

and the actual critical radius is again given by (3). The constant C depends on the height-to-diameter ratio of the cylinder and the ratio of the extrapolation distance $E(= 0.71/\beta)$ through the relation

$$C = \sqrt{2.405^2 + \left(\frac{\pi}{2}\right)^2 \left(\frac{1 + E/R_c}{H/R_c + E/R_c}\right)^2} \quad (5)$$

The procedure for calculating the critical radius of a cylinder, given B, is to assume a value for E/R_c , compute C and an estimate of critical radius, and to repeat this process until satisfactory convergence is obtained. In general, the second estimate is sufficiently accurate.

B. Physical Data

Codd, Shepherd and Tait³ list parameters α , β , and B determined experimentally for U^{235} in the Los Alamos Godiva-I reactor. These data are listed in Table I, together with nuclear constants calculated for the two alloys of interest from microscopic cross section data from BNL-325 (for molybdenum) and from Codd, Shepherd and Tait³ for U^{235} .

Table I. Nuclear Data

U ²³⁵ :	$\alpha = 0.308 \text{ cm}^{-1}$	density: 18.7 g/cm^3
	$\beta = 0.392 \text{ cm}^{-1}$	
	$B = 0.303 \text{ cm}^{-1}$	
	$\nu = 2.60$	
	$\sigma_c/\sigma_f = 0.14$	
Mo:	$\sigma_t = 8.50 \text{ bn}$	density: 10.2 g/cm^3
	$\sigma_c = 0$	
19 wt. % Mo:	$\alpha = \Sigma_t = 0.379$	alloy density: 16.14 g/cm^3
	$\beta = 0.438$	
17 wt. % Mo:	$\alpha = \Sigma_t = 0.373$	
	$\beta = 0.434$	

C. Numerical Results

Critical masses and radii for a sphere and three cylinders (of height-to-diameter ratio 0.8, 1.0, and 1.2) are listed in Table II for the 19 wt. % Mo alloy. The column labeled "5% void" gives approximate critical masses for material of 95% of full density.

Table II. Critical Masses Calculated

	Critical radius, cm	Critical mass, kg U	5% Void
Sphere	9.85	52.3	57.9
Cylinder: H/R = 0.8	9.54	57.0	63.2
H/R = 1.0	8.85	56.9	63.0
H/R = 1.2	8.42	58.8	65.2

III. BURST CHARACTERISTICS CALCULATIONS

A. Model

The one-group, one-delayed-neutron-group kinetic equation can be written in the form

$$\frac{\dot{\phi}}{\phi} = \frac{\delta - \beta_D}{\ell} \quad (6)$$

where ϕ is a suitable space-averaged neutron flux.

The assumption is made that the temperature rise is directly proportional to the total energy release which is in turn proportional to the total number of fissions, so that

$$\frac{\ddot{T}}{\dot{T}} = \frac{\dot{\phi}}{\phi} \quad (7)$$

It is further assumed that for the sphere, the radius of the sphere is given by

$$R = R_0 (1 + \alpha_T T) \quad (8)$$

and for the cylinder, the half-height is given by

$$H = H_0 (1 + \alpha_T T) \quad (9)$$

with the radius held constant. In the one-group formulation we have

$$\delta - \beta_D = \frac{\nu \Sigma_F - (\Sigma_a + D B^2)(1 + \beta_D)}{\Sigma_a + D B^2} \quad (10)$$

$$1/\ell = \bar{\nu} \left[\Sigma_a + D B^2 \right] \quad (11)$$

$$\frac{\delta - \beta_D}{\ell} = \bar{\nu} \left[\nu \Sigma_F - (\Sigma_a + D B^2)(1 + \beta_D) \right] \quad (12)$$

The cross sections vary inversely as the reactor volume, so that in the spherical case,

$$\Sigma = \frac{\Sigma_0}{(1 + \alpha_T T)^3},$$

since $V \sim R^3$, and in the cylindrical case,

$$\Sigma = \frac{\Sigma_0}{1 + \alpha_T T},$$

taking $V \sim H$. (This assumption is intended to describe the possibility that only axial density changes occur in a loose assembly of rods separated by gaps.)

Our differential equations then take the forms

$$\text{Sphere: } \frac{\ddot{T}}{\dot{T}} = \frac{A_s}{(1 + \alpha_T T)^3} - B_s(1 + \alpha_T T) \quad (13)$$

$$\text{Cylinder: } \frac{\ddot{T}}{\dot{T}} = \frac{A_c}{1 + \alpha_T T} - B_c(1 + \alpha_T T) \quad (14)$$

Making use of the approximation

$$(1 + x)^n \approx 1 + nx, \quad x \ll 1$$

yields the following expressions for the total temperature rise associated with a reactivity introduction δ_o above delayed critical:

$$\text{Sphere: } T_{\infty} = \frac{1}{2\alpha_T} \frac{\delta_o - \beta_D}{1 + \beta_D} \left(1 + \frac{1}{L_o^2 B_o^2} \right) \quad (15)$$

$$\text{Cylinder: } T_{\infty} = \frac{1}{\alpha_T} \frac{\delta_o - \beta_D}{1 + \beta_D} \left(1 + \frac{1}{L_o^2 B_R^2} + \frac{B_z^2}{B_R^2} \right) \quad (16)$$

The burst width at half maximum power is given by

$$\tau \approx \frac{3.53 \ell}{\delta_o - \beta_D} \quad (17)$$

for both cylinders and spheres.

B. Results

Burst yields are given in Table III for the "no-void" reactors listed in Table II assuming a reactivity introduction δ_o of 1% above delayed critical and a delayed neutron fraction β_D of 7.5×10^{-3} . Using an $\ell = 8.7 \times 10^{-9}$ sec, the burst width is approximately 12.3 microseconds.

Table III. Burst Yields and Temperature Rises

	Total fissions	Temperature rise, °C
Sphere	2.0×10^{17}	514
Cylinder: H/R = 0.8	6.7×10^{17}	1580
H/R = 1.0	5.2×10^{17}	1230
H/R = 1.2	4.4×10^{17}	1080

For the alloy:

$$\alpha_T = 4.3 \times 10^{-6} / \text{deg. C}; C_p = 0.182 \text{ watt sec/gm deg. C.}$$

IV. ENHANCEMENT OF THE BURST BY MECHANICAL EFFECTS IN A SIMPLE CASE

A. Formulation of the Power Burst Equation.

Using the one-group model, we may write

$$\frac{1}{v} \frac{d\phi}{dt} = -D B^2 \phi - \Sigma_a \phi + v \Sigma_f \phi \quad (18)$$

$$\text{Substituting } \frac{dF}{dt} = \Sigma_f \phi \quad (19)$$

we may write, neglecting terms of small variation:

$$L \frac{d^2 F}{dt^2} = \left[k - \beta_D - 1 \right] \frac{dF}{dt} \quad (20)$$

$$\text{where } k = \frac{v \Sigma_f}{\Sigma_a + D B^2} \quad (21)$$

$$\text{Let us assume that } k - \beta_D - 1 = \delta_0 - \beta_D + \Delta \rho \frac{dk}{d\rho} \quad (22)$$

and, further, if DB^2/Σ_a is approximately 1, we may estimate

$dk/d\rho$ as $2/3\rho_0$.

Suppose the reactor consists of a mass of small rings of very small thickness randomly interlaced so that the bulk density is that of the uranium itself. If the radius of an individual ring is R , then the fractional change in density due to thermal expansion can be shown to be

$$\frac{d\rho}{\rho} = - \frac{3dR}{R} \quad (23)$$

On the other hand, the fractional change in density due to a change in only the radius of the ring without any change in the thickness - approximately the case for the dimensional changes produced by a tangential stress - can be shown to be only $-2dR/R$. Calling the change in radius due to an

"equilibrium" rise in temperature ΔR and the amount by which the radius is compressed due to inertia ξ , the term $\frac{dk}{d\rho} \Delta\rho$ in equation (22) may be written as follows:

$$\Delta\rho \frac{dk}{d\rho} = (\Delta\rho) \left(\frac{2}{3\rho} \right) = \frac{2}{3} \left(-\frac{3\Delta R}{R} + \frac{2\xi}{R} \right) = -\frac{2\Delta R}{R} + \frac{4}{3} \frac{\xi}{R} \quad (24)$$

Now $\frac{\Delta R}{R}$, due to thermal expansion, is simply written as $\alpha_T \Delta T$. Further, neglecting heat losses, we note that

$$\alpha_T \Delta T = \frac{\alpha_T \epsilon F}{\rho c_p} = C_1 F \quad (25)$$

Substituting in equation (22) we find that

$$\delta_o - \beta_D + \Delta\rho \frac{dk}{d\rho} = \delta_o - \beta_D - 2C_1 F + \frac{4}{3} \frac{\xi}{R} \quad (26)$$

so that equation (20) now becomes

$$\ell \frac{d^2 F}{dt^2} = \left(\delta_o - \beta_o - 2C_1 F + \frac{4}{3} \frac{\xi}{R} \right) \frac{dF}{dt} \quad (27)$$

Since ξ is a complicated function of F , it was not practical to attempt to solve this equation exactly in the time available. Instead, F was determined from equation (27) with ξ neglected. Then, ξ was determined from this form of F . The maximum value of ξ so computed during the burst was substituted as a reactivity addition into (27) and the burst enhancement was calculated, assuming that this value of ξ was present only during the half-maximum time interval around the maximum value of F .

Solving equation (27) with $\xi = 0$, it is not difficult to show that

$$F = \frac{\delta_o - \beta_D}{C_1 \left(1 + e^{-(\delta_o - \beta_D)t/\ell} \right)} \quad (28)$$

provided we take time zero at the time when $\frac{dF}{dt}$ is a maximum and we assume that at time equal to $-\infty$, F and its derivatives are zero.

Let $\mu = R - R_0$ where R is the radius of the ring at any time and R_0 is the original radius. Now $R = R_0(1 + \alpha_T \Delta T) - \xi$, so that $\mu = R_0 \alpha_T \Delta T - \xi$, so that if we can find μ as a function of time we will also determine ξ . From a force balance taken on an element of the ring, assuming tangential stress only, we find that the differential equation for R is

$$\rho R_0 \frac{d^2 R}{dt^2} = Y \frac{R_0(1 + \alpha_T \Delta T) - R}{R_0(1 + \alpha_T \Delta T)} \quad (29)$$

Noting that $\alpha_T \Delta T$ is small and substituting $\mu = R - R_0$ the equation becomes

$$R_0 \rho \frac{d^2 \mu}{dt^2} + \frac{Y \mu}{R_0} = Y \alpha_T \Delta T = Y C_1 F \quad (30)$$

If we use equation (28) for F it can be shown that

$$\mu = \sum_{n=1}^{\infty} (-1)^{n-1} \frac{Y(\delta_0 - \beta_D)/R_0 \rho}{\frac{n^2(\delta_0 - \beta_D)^2}{\ell^2} + \frac{Y}{\rho R_0^2}} e^{\frac{n(\delta_0 - \beta_D)t}{\ell}}; t \leq 0 \quad (31)$$

$$\mu = \sum_{n=0}^{\infty} (-1)^n \frac{Y(\delta_0 - \beta_D)/R_0 \rho}{\frac{n^2(\delta_0 - \beta_D)^2}{\ell^2} + \frac{Y}{\rho R_0^2}} e^{\frac{-n(\delta_0 - \beta_D)t}{\ell}}$$

$$= \pi \ell \sqrt{\frac{Y}{\rho}} \cosh\left(\frac{\ell \pi}{R_0(\delta_0 - \beta_D)} \sqrt{\frac{Y}{\rho}}\right) \cos\left(\sqrt{\frac{Y}{\rho R_0^2}} t\right) \quad (32)$$

The following data were assumed for the calculation of μ :

$$Y = 22.2 \times 10^6 \text{ psi}$$

$$\delta_o - \beta_o = 0.0025$$

$$R_o = 1.07 \text{ cm}$$

$$\rho = 16.14 \text{ g/cm}^3$$

$$l = 8.7 \times 10^{-9} \text{ sec}$$

$$\alpha_T = 4.3 \times 10^{-6} / ^\circ\text{C}$$

$$C_P = 0.182 \text{ watt-sec/g } ^\circ\text{C}$$

Using these numbers, the maximum value of $\frac{4}{3} \frac{\xi}{R_o}$ was found to be 4.32×10^{-4} , which occurs very close to time zero (peak fission rate). This number was then used as a constant reactivity addition over the time interval corresponding to half-height of the unperturbed burst, with no reactivity addition before or after this time ($\pm 6.1 \times 10^{-6}$ sec). The characteristics of the burst were computed from equation (27) using data cited above. It was found that the number of fissions per cubic centimeter when ξ is assumed zero was 5.69×10^{13} , corresponding to a temperature rise of 581°C . When the reactivity addition of 4.32×10^{-4} was made in the manner described, the burst increased to 6.2×10^{13} fissions per cm^3 , an increase of 9%. This amount of energy corresponds to a temperature rise of 633°C . (The temperature rise of 581°C is to be compared with the 514°C shown in Table IV for the spherical reactor. This discrepancy was caused by differences in simplifying approximations made in the two calculations. Fortuitously, the temperature difference of 67°C is very close to the error arising from assuming that the extrapolated radius varies linearly with temperature. The higher answer would result from allowing the physical

radius and the extrapolation distance to vary in different ways with temperature.) The total fission energy released per cm^3 is 1860 watt-sec, while the total mechanical energy per cm^3 is only 0.043 watt-sec. The ratio of mechanical to total energy is much less than that which would occur in a solid assembly.

V. CONCLUSIONS

Godiva-II is limited to bursts of the order of 10^{16} due to the excessive temperature rises and stresses which would result if too much reactivity is added. The calculations reported here suggest that a layered assembly would permit much larger excursions, possibly an order of magnitude larger, to be made with safety. However, considerably more work, involving the use of high-speed computers, would be necessary to be certain of this. The present calculations have included many assumptions and simplifications, among which are the neglect of spatial variation of heat generation and a rudimentary mechanical model. The predicted bursts and temperature rises are subject to considerable error; however, the critical mass estimates should be fairly accurate, based as they are on the results for a known reactor.

TABLE IV. NOTATION

$\alpha = \Sigma_t$	=	total macroscopic cross section, cm^{-1}
β	=	$\nu \Sigma_F + \Sigma_s$
δ	=	reactivity above delayed critical
Σ_F	=	macroscopic fission cross section, cm^{-1}
Σ_s	=	macroscopic scattering cross section (inelastic + elastic), cm^{-1}
ν	=	average number of neutrons per fission
Σ_a	=	macroscopic absorption cross section, cm^{-1}
D	=	diffusion coefficient, cm
B^2	=	geometric buckling, cm^{-2}
l	=	neutron lifetime, sec
β_D	=	delayed neutron fraction
α_T	=	coefficient of linear thermal expansion, $(\text{deg C})^{-1}$
C_P	=	specific heat, watt sec/gm
T	=	temperature rise, deg C
$\dot{T}$	=	dT/dt
$\ddot{T}$	=	d^2T/dt^2
H	=	actual half-height of cylinder, cm
R	=	radius, cm; $\bar{R}$, extrapolated radius; R_c , actual radius
σ_f	=	microscopic fission cross section, barns
σ_c	=	microscopic radiative capture cross section, barns
ϕ	=	neutron flux, neutrons/ cm^2 -sec
$\bar{V}$	=	mean neutron velocity, cm/sec
F	=	total number of fissions produced per cubic centimeter up to a given time

TABLE IV. NOTATION - contd.

t	=	time, seconds
k	=	effective multiplication constant
ρ	=	density, grams per cubic centimeter
ξ	=	amount by which a dimension differs from its equilibrium (unstressed) value, length units
ϵ	=	conversion factor, 3×10^{-11} watt-seconds per fission
C_1	=	combined constant, $\alpha_T \epsilon / \rho C_p$
μ	=	amount by which a dimension differs from its initial value, length units
Δ	=	prefix to a symbol denoting a finite increment in that variable
Y	=	Young's modulus, force per unit area
V	=	volume, cm^3
A_s, B_s, A_c, B_c	=	combined constants, equations (13) and (14)

The subscript o refers to a quantity where $T = 0$.

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