OFFICIAL USE ONLY

RHM(56)113

AN ESTIMATE OF THE ORDER OF MAGNITUDE OF VIGOROUS INTERACTION EXPECTED SHOULD THE CORE OF A FAST REACTOR COLLAPSE

by

H A BETHE

J H TAIT

Report prepared for an International Discussion in April 1956

ABSTRACT

The strength of the interaction is estimated should the core of a fast reactor collapse, assuming that all the coolant has disappeared and that the core melts due to fission product heating. A number of pessimistic simplifying assumptions are made, in particular the rate of increase of reactivity is calculated assuming that the core suddenly loses its cohesion and collapses under gravity.

The pressures are estimated in a molten mass of uranium heated at constant volume, and it is shown that the core expands before it has completely vaporised.

CONTENTS

		Page
1.	INTRODUCTION	1
2.	ESTIMATE OF THE RATE OF INCREASE OF REACTIVITY SHOULD THE CORE COLLAPSE	1
3.	ESTIMATION OF THE NEUTRON DOUBLING TIME AT THE BOILING POINT	5
4.	EQUATION OF STATE OF MOLTEN URANIUM	8
5.	CALCULATION OF THE ENERGY RELEASE	9
6.	SUMMARY OF RESULTS	16
	REFERENCES	18
	DISTRIBUTION	19

1. INTRODUCTION

If the flow of coolant through a fast reactor should suddenly stop after the reactor has been running at full power, the fission product heating would be sufficient to melt the uranium in about forty seconds. There is a possibility that the molten metal might fall together and acquire a greater reactivity. The rate of increase of reactivity is not necessarily that determined by the rate of melting due to the fission product heating; this is quite slow; part of the core might melt and cause a section of the remaining structure to fall. The rate of increase of reactivity might, therefore, be determined by a core collapsing under gravity. An overestimate of this rate of increase can be obtained if we assume that the core suddenly loses its cohesion following a loss of coolant, and then commences to fall under gravity.

It should be stressed that we are not attempting to assess the probability of the occurrence of the above sequence of events; we are merely making an overestimate of the strength of the resulting explosion.

We consider a particular model of a reactor in order to assess the order of magnitude of the various quantities.

2. ESTIMATE OF THE RATE OF INCREASE OF REACTIVITY SHOULD THE CORE COLLAPSE

The reactor has a core which is a right cylinder of height 53 cms and radius 23 cms; the volume is 91 litres. The proportions by volume in the core are 50% enriched uranium, 9% canning material, 36% NaK coolant, and 5% spacing. The mass of uranium is equal to 850 kgm. The side reflector is assumed to be infinite, and to contain 65% natural uranium, 28% NaK coolant and 7% canning material by volume. The top and bottom reflectors form a continuation of the core, with natural uranium in place of enriched uranium, and are assumed to be infinite.

We shall use perturbation theory to calculate the change of reactivity should the core collapse. This theory is adequate for assessing the effect of small gaps, as can be seen from the results of calculations carried out by Codd(1) and Hines(2). Codd has calculated the effect of removing reflector material from around a spherical core, using one group modified diffusion theory and has compared the results with those obtained using perturbation theory. The results are as follows:

Gap Width in cms.	Reactivity ρ in % Calculated by Modified Diffusion theory	ρ in % Calculated by Perturbation theory
0	0	0
1	-1.46	-1.59
5	-5.99	-5.97
10	-10.1	-8.8

Hines has calculated the effect of creating a gap by the removal of core material. His results are as follows:

Gap Width in cms.	ρ calculated by M.D.T.	ρ calculated by Perturbation Theory
0	0	0
.5	-2.16	-2.20
1	-4.44	-4.42
1.5	-6.80	-6.62
2	-9.31	-8.82
2.5	-11.93	-11.02

It would seem that perturbation theory is reasonably accurate when reactivity changes are calculated due to gaps of few cms.

Codd[3] has carried out one-velocity-group perturbation theory calculations for the system which we have just described. For uniform changes $\Delta\alpha_1$ and $\Delta\beta_1$ in α_1 and β_1 over the whole core the reactivity change ρ is given as follows,

$$\rho = 41.06 (\Delta\beta_1 - .9822 \Delta\alpha_1). \tag{2.1}$$

Here α is the average number of collisions per unit length of path, and β the average number of secondaries produced per cm. If σ_S, σ_f and σ_c are the macroscopic scattering, fission and capture cross sections in cm^{-1} respectively, then

$$\alpha = \sigma_S + \sigma_f + \sigma_c,$$

$$\beta = \sigma_S + \sigma_f \nu,$$

and $(\beta-\alpha)/\alpha$ is the quantity usually denoted by f in U.S. reports.

For the core,

$$\alpha_1 = .22409 \text{ cm}^{-1}$$

$$\beta_1 = .23368 \text{ cm}^{-1}$$

If the coolant is lost $\Delta\alpha_1 = -.02337$ and $\Delta\beta_1 = -.02314$, and there is a reactivity change of $-.76\%$.

The new values of α and β are .20072 and .21054 respectively.

The amount of reactivity controlled by the delayed neutrons is $.9\%$, this being higher than the U_{235} figure owing to the fissions in the U_{238}. The total change of reactivity following loss of coolant before prompt critical is reached is, therefore, 1.66%. ✓

Suppose that a gap of thickness x appears at the top of the core. Then the reactivity drops by an amount given by the formula,

$$\rho = 10.42 \left(\frac{x}{h}\right) (\beta_1 - .9312\alpha_1), \tag{2.2}$$

where h is the height of the core.

*We assume that the density of the core increases uniformly by a factor $(1 + \frac{x}{h})$ so that the total reactivity change ρ_1, leaving out quadratic terms in x/h, is given by

$$\rho_1 = (41.06)(.21054 - [.9822][.20072]) \frac{x}{h} -$$

$$- (10.42)(.21054 - [.9312][.20072]) \frac{x}{h} . \qquad (2.3)$$

Taking the first term on the right hand side of (2.3)

$$\rho_1 = .550\ x/h .$$

This is the amount of reactivity change due to a given fractional change in size.

The total reactivity change is given by

$$\rho_1 = .304\ x/h . \qquad (2.4)$$

When $\rho = 1.66\%$, $x/h = 5.46\ 10^{-2}$, i.e. $x = 2.91$ cms.

We are assuming that the top of the core is collapsing freely under gravity.

Let t be the time when the core has fallen the distance x.

i.e.,

$$x = \tfrac{1}{2} gt^2 . \qquad (2.5)$$

---

*Strictly speaking the core is not collapsing <u>freely</u> under gravity. To achieve a uniform increase in density the top layer of the core must travel faster than the lower layers.

Differentiating (2.4) with respect to t we have,

$$\frac{d\rho}{dt} \doteq .304 \frac{\sqrt{2gx}}{h} . \qquad (2.6)$$

For our particular example,

$$\frac{d\rho}{dt} \doteq .41 \qquad (2.7)$$

i.e. the reactivity is increasing at a rate between 40 and 50 dollars per second.

3. ESTIMATION OF THE NEUTRON DOUBLING TIME AT THE BOILING POINT

We shall now determine the neutron doubling time at the moment when the core has been heated up to boiling point of uranium.

If the neutron density $N(r,t)$ is written in the form

$$N(r,t) = \bar{N}(r)\, n(t) ,$$

$n(t)$ satisifes the equation,

$$n(t) = (\beta_{pt} - \beta^*)\, vn . \qquad (3.1)$$

β^* is the value of the number of secondaries per unit path which will make the system critical, and β_{pt} is the actual number of prompt neutrons per unit path. v is the neutron velocity. In this equation we have neglected the delayed neutrons.

The multiplication rate is given by

$$\lambda = v(\beta_{pt} - \beta^*). \qquad (3.2)$$

It is related to the reactivity by (2.1) i.e.

$$\lambda = \frac{v.\rho}{41.06} = \frac{\rho}{\tau} . \qquad (3.3)$$

For the velocity we take $v = .74.10^9$ cm/secs, then the generation time τ is given by

$$\tau = 41.06/v = .56.10^{-7} \text{ sec.} \tag{3.4}$$

Near to prompt critical we assume the reactivity to vary linearly with time, as given by (2.7), and set

$$\mu = \frac{d\lambda}{dt} = \frac{1}{\tau}\frac{d\rho}{dt} = 7.4.10^6 \text{ sec}^{-2} \tag{3.5}$$

Then,

$$\dot{n} = \mu.t.n.$$

i.e. $$n = n(o).\exp\left(\tfrac{1}{2}\,\mu\, t^2\right),$$

and $$\int_0^t n(t)dt = n(o)\int_0^t \exp\left(\tfrac{1}{2}\,\mu\, t^2\right) dt,$$

$$\doteqdot \frac{n(o)}{\mu t}\exp\left(\tfrac{1}{2}\,\mu\, t^2\right), \tag{3.6}$$

if μt is large.

We shall assume that there is a certain neutron source strength in the reactor. The most dangerous state will arise when the reactor has been shut down after running at full power, so that the neutron population has died down but the fission product activity is still high.

Let us make some assumptions about $n(o)$. Following Hurwitz [4] we assume that there is a neutron source of strength 10^7n/sec, and that the fission rate at delayed critical is 10^9 fissions/sec. During the passage through the region controlled by the delayed neutrons this will increase by another factor of the order of ten, giving a power in the reactor of .3 watts.

This is equivalent to a heat production of .07 calories/second. The weight of the core is 927 kg. To raise the temperature to that of the boiling point we need 167 calories per gram*, i.e. a total of $1.6.10^8$ calories. The ratio S of this amount of heat to the rate of heat production is $2.2\ 10^9$ seconds.

Solving equation (3.4) to determine the time t_1 after prompt critical when this amount of heat has been supplied we have,

$$\frac{1}{(\mu)^{\frac{1}{2}}\, t_1} \cdot \exp(\tfrac{1}{2}\,\mu\, t_1^2) = S.\mu^{\frac{1}{2}} = 7.10^{12}.$$

i.e. $$t_1 = \left\{ \frac{2\, ln[S.\mu^{\frac{1}{2}}] + ln[2\, ln\, S\mu^{\frac{1}{2}}]}{\mu} \right\}^{\frac{1}{2}}, \qquad (3.7)$$

$$= 2.9.10^{-3} \text{ seconds},$$

and $$\lambda_1 = \mu t_1 = 2.2.10^4.$$

The e folding time is approximately 50μs. The reactivity reached is $\rho = \tau\lambda_1 = 1.2.10^{-3}$, or ·12% over prompt critical.

Suppose that S was in error by a factor of 10^6, i.e. the neutron population was 10^6 times the value which we have assumed, then

$$\mu t_1 = 1.6.10^4,$$

i.e. the error in t_1 is about 25%.

μt_1 varies as $\mu^{\frac{1}{2}}$, i.e. as $x^{\frac{1}{2}}$, it is not very sensitive to the height of the drop.

*We assume a specific heat of 10 calories/gm atom, and that the boiling point of uranium is 4000°C.

4. EQUATION OF STATE OF MOLTEN URANIUM

We wish to determine the temperature at which the collapsing core loses its porosity.

An average coefficient of volume expansion of solid uranium is $6.10^{-5}/°C$. In the liquid state the coefficient of expansion is greater, and for uranium it might be as high as $1.2.10^{-4}/°C$.

At 1200°C molten uranium has a density of 16.5, therefore the density at a temperature $T(> 1200°C)$ is equal to

$$16.5\ (1 + \alpha[T - 1200])^{-1},$$

where $6.10^{-5} < \alpha < 12.10^{-5}$.

We shall assume that the canning material is the same as the uranium. After the loss of coolant and contraction of the core, the density of the latter is 11.5. Then the temperature T_o at which the core loses its porosity is given by,

$$1 + \alpha[T_o - 1200] = 1.435.$$

If $\alpha = 6.10^{-5}$ then $T_o = 8450°C$.

If $\alpha = 12.10^{-5}$ $T_o = 4825°C$.

We assume a mean value of 6,600°C.

The amount of heat per gram necessary to bring the uranium up to a temperature of 6600°C is 275 calories i.e. $1.1.10^{10}$ ergs.

After this temperature has been reached the pressures will be set up which cause the bulk expansion of the core.

Let E be the energy supplied per unit mass to the uranium above that required to bring it up to the temperature T_o.

Then the pressure is given by the formula

$$p = (\gamma - 1) E s, \qquad (4.1)$$

where γ is the ratio of the specific heats. For the solid γ is high but for a liquid which has expanded to a density of 11, a reasonable value would seem to be 2. s is the density of the uranium.

5. CALCULATION OF THE ENERGY RELEASE

In most calculations of the energy release in an accident until now, it has been assumed that the entire core expands simultaneously. This assumption is justified in the limiting cases of either very slow or very fast accidents. In the former case the ordinary thermal expansion of the solid or liquid is sufficient to shut the reactor down; then no pressures are built up, and only the overall density of the core is important. For very fast accidents, on the other hand, pressure is built up simultaneously throughout the reactor, the pressure gradient is approximately proportional to r (cf. Eq. 5.8) and this leads to uniform expansion. This case is realied, e.g., in the N.D.A. maximum accident calculations.

In our case, however, the situation is intermediate. Inertial effects and pressure gradients are important, but the pressure is not generated simultaneously throughout the core. This is due particularly to the effect described in section 4, i.e. that first a certain temperature T_0 must be reached in order to fill all the voids left by the lost coolant, and only thereafter will further energy release build up any pressure. Therefore, large pressures will exist near the centre before any pressure is felt near the outside. The central region of the core will expand first, while the edge remains at rest, and we shall have to calculate the effect on the reactivity of such a local expansion. The material displaced from the centre will of course accummulate somewhat farther out, and there will be a "pressure wave" travelling outwards (not with the speed of sound).

We consider a spherical model. The neutron flux is assumed to vary as $1 - q\, r^2/b^2$ in the core, where b is the core radius. The value of q is calculated to give approximately the variation of flux which occurs in the actual reactor and is equal to .6.

Let R be the co-ordinate of an element which was originally given by the co-ordinate r before the expansion commenced. The diffusion equation in the Euler co-ordinate R is then as follows:

$$\frac{1}{3R^2}\frac{d}{dR}\left(l_{tr} R^2 \frac{d\tilde{N}}{dR}\right) + \frac{\tilde{N}}{l_{rep}} = 0 , \tag{5.1}$$

where l_{tr} and l_{rep} are the transport and reproduction mean free paths respectively.

If the material density has altered by a factor θ then the mean free paths change by a factor of $1/\theta$, i.e.

$$\frac{1}{\theta R^2}\frac{d}{dR}\left(\frac{R^2}{\theta}\frac{d\tilde{N}}{dR}\right) + K^2\tilde{N} = 0 . \tag{5.2}$$

K^2 is the value of the Laplacian of the core before the expansion stage. Now K^2 can be written as,

$$K^2 = 3\alpha_o\,(\beta - \alpha_o) ,$$

where α_o is the original inverse mean free path, and β is the number of secondaries per unit path.

Consider the original density $\tilde{N}_o$ (before collapse) which satisfies the equation:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\tilde{N}_o}{dr}\right) + K_o^2\tilde{N}_o = 0 , \tag{5.3}$$

where $K_o^2 = 3\alpha_o\,(\beta_o - \alpha_o)$.

β_o is the number of secondaries per unit path such that the original system is just critical, and the change in criticality when the expansion has occurred is measured by $\beta - \beta_o$.

Now,

$$\dot{\theta}\, R^2\, dR = r^2 dr \text{ (The equation of continuity).}$$

Let $R = r + u, \quad u \ll r$.

Then (5.2) becomes,

$$\frac{1}{r^2}\frac{d}{dr}\left(\frac{R^4}{r^4}\, r^2 \frac{d\tilde{N}}{dr}\right) + K^2 \tilde{N} = 0.$$

i.e. $$\frac{1}{r^2}\frac{d}{dr}\left(\left[1 + \frac{4u}{r}\right] r^2 \frac{d\tilde{N}}{dr}\right) + K^2 \tilde{N} = 0.$$

From (5.3) and (5.5) we have,

$$\int r^2 (K_o^2 - K^2)\, \tilde{N}_o \tilde{N}\, dr + 4 \int \tilde{N}_o \frac{d}{dr}\left(u\, r \frac{d\tilde{N}}{dr}\right) dr = 0.$$

Therefore,

$$\frac{K_o^2 - K^2}{K_o^2} = \frac{\dot{\beta}_o - \dot{\beta}}{\beta_o - \alpha_o} = 2.54\rho = - \frac{4 \int u r \left(\frac{d\tilde{N}}{dr}\right)^2 dr}{\int r^2 \left(\frac{d\tilde{N}}{dr}\right)^2 dr},$$

where ρ is the reactivity change corresponding [illegible].

We have neglected changes in the neutron density. The integrals are over space including the tamper, but $u \neq 0$ only in the core.

Now $$\tilde{N}_o = 1 - q\frac{r^2}{b^2},$$

i.e. $$\frac{d\tilde{N}_o}{dr} = -2q\frac{r}{b^2}.$$

For simplicity, we assume that (5.8) holds until $n = 0$, i.e. into the tamper to a point r_2 given by

$$r_2/b = 1/\sqrt{q} .$$

This overestimates the denominator of (5.7), i.e. underestimates ρ and overestimates the energy release.

We obtain,

$$\int_0^{r_2} r^2 \left(\frac{d\tilde{N}_o}{dr}\right)^2 dr = \frac{4b}{5\sqrt{q}} . \qquad (5.9)$$

Let us now consider the calculation of u.

The equation of motion is

$$\ddot{u} = -\frac{1}{s}\frac{\partial p}{\partial R}, \text{ (dot denotes differentiation with respect to } t)$$

$$= \frac{R^2}{s \cdot r^2 \cdot \dot{\theta}} \frac{\partial p}{\partial r},$$

$$\doteq -(\gamma - 1)\frac{\partial E}{\partial r}, \qquad (5.9a)$$

using equation (4.1).

Now $E = Q(r,t) - Q^*$,

where Q^* is the amount of heat required to bring the uranium up to a temperature T_o.

$$Q(r,t) = Q(t)\,(1 - q\, r^2/b^2) \qquad (5.10)$$

where $Q(t)$ is the heat release per gram at the centre.

Therefore,

$$\ddot{u} = +(\gamma - 1)\frac{2qr}{b^2}Q(t) \tag{5.11}$$

This equation is applicable after $Q(t)$ has exceeded Q^*. To integrate the equation we assume that $Q(t) = Q^*$, i.e. we underestimate the acceleration and overestimate the explosion.

Therefore,

$$u = Q^*(\gamma - 1)\frac{qr}{b^2}\left(t - t_o(r)\right)^2, \tag{5.12}$$

where $t_o(r)$ is the time when the pressure is commencing to build up at the point r.

To determine $t_o(r)$ we have to solve the equation

$$Q[t_o(r)] \,.\, (1 - q\, r^2/b^2) = Q^*. \tag{5.13}$$

Let us now discuss how $Q(t)$ varies with time. The time when the pressure commences to build up at the centre of the core will be very nearly equal to t_1 (see 3.7). After, this time t_1 the neutron density will still increase until the system is brough back to critical. $Q(t)$ like the neutron density n increases essentially exponentially as $e^{\lambda t}$, and λ is nearly equal to λ_1 at the beginning of the expansion stage. The heat generated after t_1 at the centre is given by,

$$Q^*\,[e^{\lambda_1(t-t_1)} - 1]. \tag{5.14}$$

From (5.13) and (5.14) we find,

$$e^{\lambda_1(t_o-t_1)} = \frac{1}{1-qr^2/b^2}, \tag{5.15}$$

i.e.

$$\lambda_1(t_o-t_1) = -\ln\,(1 - q r^2/b^2)$$

$$\doteq q\frac{r^2}{b^2} + \frac{1}{2}q^2\frac{r^4}{b^4} \tag{5.16}$$

In (5.12) let t be the time when the pressure begins to build up at r_1.

Then,

$$\lambda_1 . [t - t_o(r)] \doteqdot q \frac{r_1^2}{b^2} + \frac{1}{2} q^2 \frac{r_1^4}{b^4} - q \frac{r^2}{b^2} - \frac{1}{2} q^2 \frac{r^4}{b^4}.$$

Substituting into (5.12) we have,

$$u = Q^*(\gamma - 1) \frac{qr}{\lambda_1^2 b^2} \left[q \frac{r_1^2}{b^2} + \frac{1}{2} q^2 \frac{r_1^4}{b^4} - q \frac{r^2}{b^2} - \frac{1}{2} q^2 \frac{r^4}{b^4} \right]^2$$

Let us calculate the value of the integral which occurs in the numerator of (5.7):

$$4 \int u.r.(\frac{d\tilde{N}_o}{dr})^2 dr = \frac{16.Q^*(\gamma-1)q^3}{\lambda_1^2 \quad b^6} \int_0^{r_1} r^4 \left[q \frac{r_1^2}{b^2} + \frac{1}{2} q^2 \frac{r_1^4}{b^4} - q \frac{r^2}{b^2} - \frac{1}{2} q^2 \frac{r^4}{b^4}\right]^2 dr$$

$$\doteqdot \frac{16 \; Q^*(\gamma-1) q^5 \; r_1^9}{\lambda_1^2 \; b^{10}} \left[\frac{1}{40} + \frac{q \; r_1^2}{27 b^2} + \frac{1}{73} q^2 \frac{r_1^4}{b^4}\right], \qquad (5.17)$$

Substituting into (5.7)

$$2.54 \rho = -\frac{Q^*(\gamma-1) \; q^{5.5}}{2 \; b^2 \lambda_1^2} \left(\frac{r_1}{b}\right)^9 \left[1 + 1.48 \frac{q \cdot r_1^2}{b^2} + .55 \; q^2 \frac{r_1^4}{b^4}\right]. \qquad (5.18)$$

For the system to return to prompt critical the reactivity must change by $-1.2.10^{-3}$.

$\frac{r_1}{b}$ is given by,

$$\left(\frac{r_1}{b}\right)^9 \left[1 + 1.48 \frac{q \; r_1^2}{b^2} + .55 q^2 \frac{r_1^4}{b^4}\right] = 2.79. \qquad (5.19)$$

i.e. $\frac{r_1}{b} \doteqdot 1.03$.

This means that the pressure wave has just arrived to the edge of the core when the system returns to prompt critical.

The heat generated $Q(r,t)$ at r is given by,

$$Q(r,t) = Q(t).(1 - q\frac{r^2}{b^2}),$$

$$= Q^*.e^{\lambda_1(t-t_1)}(1 - q\ r^2/b^2).$$

When the pressure wave has reached r_1, using (5.15) we have

$$e^{\lambda_1(t-t_1)} = \frac{1}{1-qr_1^2/b^2}.$$

Therefore,

$$E(r,t) = Q(r,t) - Q^*,$$

$$= \frac{Q^*.q.(r_1^2-r^2)}{b^2(1-qr_1^2/b^2)} \qquad (5.20)$$

The total disposable energy W generated up to prompt critical is given by

$$W = \frac{4\pi.s.Q^*}{1-qr_1^2/b^2}\int_0^{r_1} r^2\,dr\,(r_1^2 - r^2)\frac{q}{b^2}, \qquad (5.21)$$

where s is the density of the uranium.

$$W = \frac{4\pi s}{3}\,b^3 . \frac{2}{5}\,\frac{q.r_1^5/b^5\,Q^*}{1-q\ r_1^2/b^2}, \qquad (5.22)$$

$$W = M.w$$

where M and w are the mass and the energy released per unit mass respectively.

For $q = .6$ and $r_1/b = 1$, this gives

$$w = .6Q^*$$
$$= .66.10^{10} \text{ ergs/gram}$$

The centre has a disposable energy of $E = Q^* \left(\frac{1}{1-q} - 1\right) = 1.5\,Q^*$, i.e. $1.7.10^{10}$ ergs/gram and intermediate energy points have less disposable energy.

The speed at which the pressure wave travels out can be easily determined.

If we differentiate (5.15) with respect to t_o we obtain

$$\frac{dr}{dt_o} = \frac{\lambda_1 \left(1 - q\frac{r^2}{b^2}\right)b^2}{2qr} \qquad (5.23)$$

When $r = b$, $\frac{dr}{dt_o} \doteqdot 2.10^5$ cms per second.

This is an underestimate of the speed at which the pressure wave travels out, it is considerably greater than this for small r. As the velocity of sound in uranium at low temperatures is 2.10^5 cms., it would seem that the method which has been used to evaluate the energy release is correct.

6. SUMMARY OF RESULTS

We have shown that when the core of a fast reactor collapses, the reactivity might increase at a rate of between 40 and 50 dollars per second. When enough heat has been generated in the system to raise the uranium to its boiling point, the system will be 13 cents over prompt critical.

The rate of increase of reactivity is proportional to the square root of the gravitational drop, and the amount by which the system is over prompt critical is proportional to the fourth root of the drop.

An error of 10^6 can be made in estimating the source strength before collapse without affecting these quantities by any great factor.

The energy release per gram of material w is related to the various quantities by the approximate relation

$$w = \frac{A.(Q^*)^{\frac{1}{2}}\ \lambda_1 . b . \rho^{\frac{1}{2}}}{(\gamma-1)^{\frac{1}{2}}\ q^2} \qquad (6.1)$$

where A is a constant.

This relation is obtained by altering the terms $q^{5.5}$ and $\left(\frac{r_1}{b}\right)^9$ in (5.18) to q^6 and $\left(\frac{r_1}{b}\right)^{10}$ neglecting higher powers of $\frac{r_1}{b}$ and substituting into (5.22). The term $1 - q\ r_1^2/b^2$ is assumed to be constant and approximately equal to $1-q$.

We made an approximation in integrating (5.11), the final answer will include the square root of any error.

Now λ_1 varies as $\mu^{\frac{1}{2}}$ and ρ as $\tau\lambda_1$, therefore from 3.5,

$$\rho \sim \sqrt{\tau \frac{\partial\rho}{\partial t}}\ .$$

So that the term $\lambda_1\rho^{\frac{1}{2}}$ in (6.1) varies as $\frac{\rho^{\frac{3}{2}}}{\tau}$, i.e. as $\tau^{-\frac{1}{4}}(\frac{d\rho}{dt})^{\frac{3}{4}}$. Thus the dependence on the neutron generation time is very weak, $\tau^{-\frac{1}{4}}$; and on the rate of increase of reactivity not very strong ($\frac{3}{4}$ power). Since the latter varies as $\sqrt{x}$, the dependence on the height of the drop is $x^{\frac{3}{8}}$.

The energy release of $.66.10^{10}$ ergs per gram will produce pressures of the order of those occurring in T.N.T. The energy release is, therefore equivalent to the explosion of 160 kg of T.N.T.

REFERENCES

(1) J. Codd and Miss J. Egerton. "The effect of a gap between the core and reflector of a fast reactor". Harwell Memorandum RP/M.36.

(2) K. C. Hines. "The effect of creating a gap between the core and reflector of a fast reactor by the removal of core material". Harwell Memorandum RP/M.64.

(3) J. Codd. "Perturbation theory calculations for the Dunreay fast reactor". Harwell Memorandum RP/M.60.

(4) H. Hurwitz, Jr. "Safeguard considerations for nuclear power plants". Nucleonics March 1954, Vol.12. No.3.

DISTRIBUTION

G. W. Wensch

Dr. Willis
Sir John Cockcroft
Dr. B. F. J. Schonland
Mr. G. W. Raby
Dr. J. V. Dunworth
Mr. H. W. Bowker
Mr. A. C. Chamberlain
Mr. J. Codd
Mr. H. J. Dunster
Mr. F. W. Fenning
Dr. B. H. Flowers
Mr. G. W. K. Ford
Mr. T. M. Fry
Mr. H. J. Grout
Dr. A. Hassitt
Mr. R. F. Jackson
Dr. W. G. Marley
Mr. C. A. Rennie
Mr. R. J. Royston
Dr. L. R. Shepherd
Mr. N. G. Stewart
Dr. J. B. Sykes
Dr. J. H. Tait
Mr. J. Walker
Mr. R. T. P. Whipple
Mr. D. V. Wordsworth

U.S.A.E.C., through Dr. Willis, British Embassy, Washington.
British Embassy, Washington.
A.E.R.E.

DISTRIBUTION (Continued)

Mr. P. T. Fletcher	Risley
Mr. F. R. Farmer	"
Mr. I. Bowen	"
Mr. J. Tatlock	"
Mr. H. G. Davey	Windscale
Mr. D. Clark	C.E.A., Chief Eng. Dept., Bankside House, Sumner Street, London S.E.1.
Mr. G. P. Smedley	Lloyd's Register of Shipping, 71 Fenchurch Street, London E.C.3.
APDA, 2000 Second Avenue, Detroit, c/o Mr. Walter McCarthy	
Nuclear Development Corporation, c/o Dr. Geortzel	5, New Street, White Plains, N.Y.
Dr. Thalgott	Argonne National Laboratory
Dr. Hugh Paxton	Los Alamos Laboratory
Dr. Harvey Brooks	Cruft Laboratory, Cambridge 38, Mass.
Dr. Edward Teller	Physics Dept., University of California, Berkeley, California.