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Addendum to
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EFFECT OF MELTING FAST CORE OF INTERNAL
EXPONENTIAL EXPERIMENT

by

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Addendum to

ANL-5547 - Summary Report of the Hazards of the Internal
Exponential Experiment (ZPR-V)

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July 16, 1956

EFFECT OF MELTING FAST CORE OF INTERNAL EXPONENTIAL EXPERIMENT

It was pointed out in the Hazards Summary Report for the Internal Exponential Experiment, ANL-5547, that the possibility existed of forming a fast super-critical assembly by melting down the fast core as a result of a runaway of the combined fast-thermal system. This could lead to a low-order nuclear explosion. It is the purpose of this memorandum to provide a more detailed discussion of this possibility.

A catastrophe of this nature would be the consequence of a fast-thermal excursion of the order of 100 cal/cc in the annulus, followed by steady boiling at a power estimated at 29 cal/cc/sec. It is assumed that all controls have failed so that boiling proceeds unchecked. A more energetic burst than about 100 cal/cc would correspond to a period of 10 milliseconds or less and would probably result either in complete expulsion of water from the core, or, for periods of about 2 milliseconds, in destruction of the reactor. As a result of the heat input the core would melt, adding reactivity that would result in one or more additional thermal bursts. This burst would possibly be energetic enough to destroy the reactor, in which case no fast critical assembly would be formed. However, it is conceivable that in the burst the remaining water would merely be expelled from the annulus, with enough heat supplied in the core to complete melting.

The fast core at a 5:1 U^{238} to U^{235} ratio contains per cc. 1.06 g of U^{235} , 3.3 g of U^{238} in the fuel plates; and 2.0 g of U^{238} in dilution plates. Also present is 0.8 g/cc of Fe and, usually,

0.4 g/cc of Al. The heat that must be supplied to raise U from room temperature to the melting point is 50 cal/gm, and the heat of fusion is 20 cal/gm. The specific heat of the liquid is assumed to be 10 cal/mol-°C or 0.042 cal/gm-°C. About 80% of the core power is evolved in the U^{235} and 7% in the U^{238} of the fuel plates. It is assumed that the power density in the core is the same as the annulus; this will usually be conservative. Powers are given for the maximum of the vertical cosine distribution; the minimum will be about 0.6 of these.

It is seen that an initial burst of 100 cal/cc would be nearly enough to melt the U^{235} in the fuel plates. During the ensuing steady boiling the melting of the U^{235} would be completed and, when several hundred degrees of superheat was present, melting of the U^{238} in the fuel plates would commence at an appreciable rate. For the U^{235} to acquire 500° C superheat would require about $\frac{1.06 \times 0.042 \times 500}{29 \times 0.8} = 1 \text{ sec.}$

The total heat necessary to melt the fuel plates is 306 cal/cc (this is larger than stated in ANL-5547 because too low a value of the heat of fusion was used there). A steady boiling period of 7 seconds would be required to supply this heat. During this time the molten U^{235} would be held between the U^{238} plates in the fuel plates by surface tension. After this head had been supplied the plates would start sagging in the middle and molten U would drip to the sides and bottoms of the fuel cans. Because of the eutectic of U and Fe, the melting point of which ranges between 700° and 1130° C, molten U rapidly attacks Fe. It has been observed by members of the Argonne Metallurgy Division that molten U will eat through a 1/2 inch thick Fe plate in about 30 seconds. It is considered unlikely that the top parts of the fuel plates would fall to the bottoms of the cans

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before the material in the lower parts of the cans was melted, because of small clearances involved. Probably a mass of molten material would form in the center of the cosine distribution, and would sag and drip down over a period of seconds.

The reactivity change that would occur when the core started to sag is difficult to estimate because of the complicated geometry of the resulting systems. The increased reactivity caused by concentration of the fast fuel is at least partially offset by opening of a gap between core and top reflector, and by the decreased importance of the upper part of the annulus. Because of these effects it is probable that nothing would happen to change the steady boiling condition of the runaway until the top of the fuel had sagged some 10 or 20 cm, although it is impossible to determine exactly what would happen after this, both because the rate of additions of reactivity cannot be accurately forecast and because data from the Borax experiments do not exist for the situation in question. The addition of reactivity would, at most, be at a rate of the order of several per cent per second. This would probably result in a series of chugs, the energy of which would accelerate melting of the core.

Let it now be assumed that as a result of the runaway the annulus reactivity has been removed while the fast core contains enough heat to become molten. In ANL-5547 two cases were considered: in one the core was assumed to melt uniformly, while in the other only the lower parts of the natural U dilution plates and of the cans were considered to be involved. The second is more pessimistic, although there is not much difference in criticality of the resulting assemblies. In the latter case the melted core would contain 90 volume per cent U with 3.7:1 ratio of U^{238} to U^{235} , and 10 per cent Fe. The radius was assumed

to be 28 cm and the height of the melt would be about 19 cm. (It was incorrectly stated in ANL-5547 to be 29.4 cm). The critical mass of the fully reflected melt, using a shape factor of 1.20 to correct from $L/D = 1$ to 0.38, is estimated as 123 kg. at a core density corresponding to a pure U density of 18.7. The actual density at the U melting point would correspond to a pure U density of 16.5. Critical masses for fully reflected assemblies have been found in Los Alamos experiments to vary with core density ρ as $\rho^{-1.2}$. This correction would increase the critical mass to $123 \times (18.7/16.5)^{1.2} = 142$ kg. However, it is possible for the melt to form at the U-Fe eutectic temperature of 725° C. This would correspond to a density for pure U of 17.5 or a critical mass of $123 \times (18.7/17.5)^{1.2} = 133$ kg.

It is unrealistic to assume that the molten core could collapse very rapidly without considerable superheat. To raise the reflected critical mass to 155 kg. a pure U density of 15.4 would be required, corresponding to a melt temperature of about 2000° C. This would correspond to 13% voids in the 725° C melt or to 7% voids in a melt at 1200° C.

The above discussion assumes that the assembly is completely reflected. Actually it is believed that the top reflector will not fall immediately because the cans will be jammed fairly tightly together and a certain amount of melting and refreezing will take place. The heat release near the reflector will become small as the fuel drops away from it. It is estimated that the worth of the top reflector is 9% k or about 5 cm of core height. Without this reflector, therefore, all critical masses are multiplied by $24/19$. Then a melt at 1200° C would have an estimated critical mass of $142 \times 24/19 = 180$ kg and would probably not be critical. The question naturally arises as to what would happen if

a subcritical melt cooled and became supercritical as a result. Since cooling would be slow under these conditions, the reactivity addition rate would be too slow to cause a significant explosion. The melt would probably eat through the 1/2 inch iron tank and run out before much cooling could occur. A steam explosion would result from this if water was still present in the annulus.

The excursion that would result from the falling of the reflector on a subcritical melt with the consequent formation of a supercritical fast assembly has been calculated for us by R. O. Brittan. His calculations⁽¹⁾ are based on the solution of a one-group space-independent kinetic equation with the reactivity determined as a function of time by the equation

$$dk/dt = A + B n(t)$$

where $n(t)$ is neutron density as a function of time. This solution can be used only if A and B are constants for the problem under consideration and if inertia effects can be neglected in calculating energy release. It is Brittan's opinion, based on previous experience, that inertia effects in the core will not be significant for the range of reactivity insertion rates applicable to this problem. Then as long as the reflector is not in contact with the molten core a free surface exists at the top of the core which allows instantaneous expansion and cancellation of the reactivity introduced by the approaching reflector. After the core and reflector are in contact, Brittan's solution no longer strictly applies. It will be seen, however, that the effect of the reflector inertia will be insignificant.

The system is assumed to become delayed critical when the reflector is 10 cm above the core. From this point on reactivity is assumed to be added at the rate of 0.9% per cm times the velocity of approach in cm to the original position of the top of the core

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$$A = 0.009 \text{ v}$$

The total worth of the reflector is 9%, and the effect of the gap is estimated to be such that it will cause reactivity to be added linearly over at least 10 cm.

The decrease in reactivity of the system caused by expansion of the unreflected core is calculated to be 1.65% per cm. However, when the reflector is near the core the narrowing of the gap caused by expansion of the core gives an increase of 0.9% per cm, giving a net decrease of 0.75% per cm. The coefficient of volume expansion of the melt is estimated as $9 \times 10^{-5}/^{\circ}\text{C}$. As expansion is only possible in the vertical direction and as the initial melt height is 19 cm, one obtains

$$dh/d\theta = 19 \times 9 \times 10^{-5} = 1.71 \times 10^{-3} \text{ cm}/^{\circ}\text{C}$$

for the change in core height with temperature. The initial power is estimated to be 0.01 cal/gm-sec. furnished by delayed neutrons from the burst that completes melting of the core.

The temperature rise above the melting point is related to the energy release by

$$\theta \text{ (.045 cal/g-deg)} = (.01 \text{ cal/gram sec}) \int_0^t n/n_0 \, dt.$$

The rate of temperature rise is then

$$d\theta/dt = 0.22 \, n/n_0 \text{ degrees C per second}$$

The term Bn can be expressed as

$$\begin{aligned} Bn &= Bn_0 \, n/n_0 = (dk/dh) (dh/d\theta) (d\theta/dt)_{\text{initial}} \, n/n_0 \\ &= (-0.0075) (1.71 \times 10^{-3}) (.22) \, n/n_0 = (2.8 \times 10^{-6}) \, n/n_0 \end{aligned}$$

In Brittan's solution, A and $B n_0$ appear as parameters. In the range of interest here the power as a function of time first goes through a burst and then falls because the core expands and subtracts reactivity more rapidly than the falling reflector can add it. This process is

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repeated with weaker bursts gradually dying out, the reactivity oscillating about prompt critical. The curves have similar shapes for different values of parameters, the oscillation becoming more violent and lasting longer for more rapid reactivity insertion rate and weaker shutdown. (See Fig. 7, 8 and 9 of ANL-5577.)

A reasonable picture of the approach of reflector and core is that first the bottom 20 cm of a can is dissolved by the molten U, allowing the can to sink down so that the reflector section is about 20 cm above the melt. The next 20 cm of can is then attacked, finally allowing the reflector section to sink to the top of the melt. The time scale for attacking the cans can be judged roughly by the 30 seconds required to eat through 1/2 inch of iron. One would guess that two or three seconds would be the order of magnitude of time for dissolving the 65 mil cans. It is unreasonable to suppose that all the reflector sections would approach the core at the same instant. In fact, some of the upper parts of the cans will probably be attacked in forming the melt, depending on how the U tends to sag and drip down. The time required for a reflector section to make a free fall over the last 10 cm of gap starting from rest at 20 cm above the core is $\sqrt{40/980}$ - $\sqrt{20/980}$ = 0.202 - 0.143 = 0.059 sec. It seems unreasonable, however, to assume that the reflector sections will all cover the last 10 cm of gap within such a short time interval. An interval of 0.2 to 0.5 seconds is more realistic. This corresponds to an average velocity of approach of 20 to 50 cm a second, or an A of 0.18 to 0.45.

The history of the resulting excursion may be followed from Figure 1. Here the shutdown reactivity, $B \int n dt$, and the temperature rise, θ , which is also proportional to $\int n dt$, are plotted as a function of the applied reactivity, $A t$. These results are dependent on A only

in that for smaller A the wiggles in the curve are damped out faster. The calculation was actually carried out for $A = 1.8$ (the case of free-falling reflector), so that for the reactivity range applicable here the smooth part of the curve will be reached sooner. In the smooth portion of the curve the reactivity $A t$ introduced by the approach of the reflector exceeds the shutdown reactivity by β , the power level being constant. The time scale is too short for the delayed neutrons to enter in. The power is equal to $n/n_0 \times$ initial power, where since

$$k = \beta = A t + B n_0 \int n(t)/n_0 dt,$$

$$n/n_0 = - A/Bn_0 = + A/2.8 \times 10^{-6}$$

For $A = 0.45$, $n/n_0 = 1.61 \times 10^5$

$$d\theta/dt = 0.22 \times 1.61 \times 10^5 = 3.54 \times 10^4 \text{ } ^\circ\text{C/sec}$$

$$dh/dt = d\theta/dt \times dh/d\theta = 3.54 \times 10^4 \times 1.71 \times 10^{-3} = 61 \text{ cm/sec}$$

The core and reflector meet when the reactivity introduced by closing the gap less β (assumed to be 0.0075) has been balanced by expansion of the core. The core must then expand $0.0825/0.0165 = 5.0$ cm, and the temperature of the molten core must rise $5.0/1.71 \times 10^{-3} = 2920^\circ \text{ C}$.

If the melt was originally at 1200° C , this would take the temperature 200° C above the atmospheric boiling point. However, this would correspond to a vapor pressure of only several pounds above atmospheric. The melt could be expected to be under this much pressure from heated air. If the reflector sections are actually incapable of maintaining pressure above the core, the upper surface of the melt will be effectively free at all times and the inertia of the reflector can be neglected.

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When the reflector hits the core the inertia of the former must be taken into account. It is assumed that the system shuts down at 2% below prompt critical, which corresponds to a motion of the top of the core of 1.2 cm. Without hindrance from the reflector this would be accomplished in $1.2/61 = 0.020$ sec, with a temperature rise of $1.2/1.71 \times 10^{-3} = 700^\circ \text{C}$. The acceleration required to move the reflector a distance of 1.2 cm in 0.020 secs is $a = 2s/t^2 = 2.4/4 \times 10^{-4} = 6000 \text{ cm/sec}^2$
 $p = ma$, where $m = 406 \text{ gms/cm}^2$

$$= 406 \times 6000 = 2.4 \times 10^6 \text{ dynes/cm}^2$$

$$= 2.4 \text{ atmospheres}$$

The equation of state for molten U suggested by Bethe and Tait⁽²⁾ yields a pressure coefficient of energy at constant volume of 580 atmospheres per cal/gm, so that the effect of the reflector on the energy production in the excursion is negligible.

The total heat necessary to melt the 930 kg of U and 130 kg of Fe in the fast core at 1200°C is $70 \text{ cal/gm} \times 9.3 \times 10^5 \text{ gms} + 186 \text{ cal/gm} \times 1.3 \times 10^5 \text{ gms} = 65 \times 10^6 + 24 \times 10^6 = 89 \times 10^6 \text{ cal} = 375 \text{ megawatt/sec}$. It is assumed that the same amount of heat is generated in the annulus. The annulus steam explosion would not constitute a significant radiation hazard over several hundred feet from the reactor, according to the Borax I experience for a 155 megawatt sec. explosion. The only consequence of the fast excursion discussed here would be the vaporisation of a small part of the melt. The superheat of the liquid above the 3900°C boiling point would be 900°C , or $900 \times 0.045 = 41 \text{ cal/gm}$. The heat of vaporisation is about 390 cal/gm, so that about 10% of the melt is vaporized. in cooling down to the atmospheric boiling point. The total fission energy produced in the melt is $2.6 \times 10^8 \text{ cal}$, representing the heat necessary to go from solid at room temperature so that 10% of this would

be present in the vapor. For the remaining melt about 25% of the fission product activity is gaseous and would be evolved, giving a total of about 9×10^7 cal of activity in the form of a cloud. In ANL-5547 a calculation based on 3.4×10^8 cal of activity in the cloud, gave, for a dose limit of 300 r, an exclusion radius of 2400 ft. The 9×10^7 cal activity in the cloud would correspond to an exclusion radius of 1300 ft. as calculated by the methods of WASH-3. (3)

The cloud gamma dosage may also be estimated from the monograph in "Meteorology & Atomic Energy," (4) for a power excursion resulting in 379 Megawatt/sec (9×10^7 cal) in the cloud assuming a height of zero meters, a mean wind velocity of 13.4 meters/sec (30 miles per hour), a Sutton stability index of 0.5, and a Sutton diffusion parameter of .05. In this manner it is found that the dosage is 150 roentgens at 400 meters (1300 ft.).

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R. O. Britten.
2. RHM (56) (113) - "An Estimate of the Order of Magnitude of the
Explosion When the Core of A Fast Reactor Collapses." H. A. Bethe
and J. H. Tait.
3. WASH-3 - Summary Report of the Reactor Safeguard Committee.
4. AECU-3066 - Meteorology and Atomic Energy.

FIG. 1

A = RATE OF INTRODUCTION OF REACTIVITY / TIME

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