The definition of the critical mass has nothing to do with the presence of an extraneous source. The ion temperature (10 keV) is again too high, and probably in this case $\lambda = \beta_2 > (\alpha_2\beta_1)^{1/2}$, which means that for such a temperature the plutonium triggering is no longer necessary, and the pure thermonuclear system is able to grow exponentially. From the ignition point of view the fissile core is useful only if the compression does not bring DT to a temperature high enough for thermonuclear self-ignition.

Returning to Ref. 1 and the compression energy requirement, we agree with the value given by Cole and Renken. It is rather high, ~10 MJ, and is only a part of the total input energy (of order 1/10). Nevertheless, the gain on the fission side only is on the order of 1000 (Ref. 4).

In conclusion, we think that it would still be interesting enough to consider dry ^{6}LiD-reflected ^{239}Pu pellets for a high-yield-per-pulse system. However, one should think simultaneously about the containment problems that have to be solved even for energy yields on the order of 10^{10} to 10^{11} J (equivalent to 2.5 to 25 tons of TNT). The so-called "falling evaporating molten-salt blanket concept"[10] is one very promising possibility for an effective blast wave attenuation, so that the containment volume has reasonable technical dimensions. Furthermore, machines to produce highly intensive beams of relativistic electrons, ions, or neutrals have to be developed[11] to provide the necessary beam energy to initiate the gas dynamic ablation process in an outer shell of the pellet to compress the whole system. After the solution of all these problems, there might be a peaceful use of the microbomb system described that resembles, on a microscale, large hydrogen bombs. But then it would be perhaps better to speak about "miniexplosions" rather than "microexplosions."

J. Ligou
W. Seifritz

Swiss Federal Institute for Reactor Research
Würenlingen, Switzerland

February 9, 1976

[10]W. SEIFRITZ and H. NAEGELE, *Trans. Am. Nucl. Soc.*, **21**, 18 (1975).

[11]M. V. BABYKIN, "Plasma Heating by High Power Relativistic Electron Beams," Seventh Conf. Controlled Fusion and Plasma Physics, Lausanne, September 1-5, 1975.

Response to "Comments on 'Analysis of the Microfission Reactor Concept' "

We are in substantial agreement with the comments of Ligou and Seifritz,[1] but would like to clarify two points.

Equation (8) in our original paper,[2]

$$N_0 \exp\left[\int_{t_c}^{t_c+\tau_l} \alpha(t')\,dt'\right] \approx N_A \quad , \tag{8}$$

was perhaps not adequately discussed there. We wanted to derive a simple estimate of the Rossi-α (or degree of supercriticality) necessary to achieve an explosive yield without entering a discussion of dynamics. It is necessary (but not sufficient) that Eq. (8) be satisfied. With the observation that the integral is *at most* $\approx \frac{1}{2}\,\alpha_{max}\,\tau_l$, this leads to the requirement

$$R_c\,\alpha_{max} \gtrsim 2v_s \ln (N_A/N_0) \quad .$$

This is admittedly a very rough lower bound on α_{max}; the point is that for *no* dynamic development could the necessary α_{max} be substantially smaller. We agree that an explosive excursion will be terminated by burnup rather than by disassembly and wish to point out that the integral in Eq. (8) is therefore $\approx \frac{1}{2}\,\alpha_{max} t_{burnup} < \frac{1}{2}\,\alpha_{max}\,\tau_l$, which increases the requisite α_{max}. The logarithmic dependence of α_{max} on the initial neutron population N_0 is so weak that increasing N_0 from our value of 10^3 to the Ligou and Seifritz value of 10^{15} reduces the required α_{max} by only a factor of ~3. Interestingly, this is close to the ratio of our estimate, 3.5×10^{10} sec^{-1}, to their 1.47×10^{10} sec^{-1}.

With regard to the effectiveness of neutron-reflecting layers in reducing the size of explosively supercritical assemblies, there is actually no real difference of opinion between Ligou and Seifritz and ourselves. The *apparent* difference is simply a matter of interpretation and emphasis. Our precise statement was that a reflecting layer "does not significantly reduce the work necessary to produce a fission yield from a fractional-gram pellet."[2] Compared to the several orders of magnitude by which the work requirement must be reduced to achieve commercial practicality—or even near-term possibility—10 or 20% cannot be considered at all significant and a factor of 2 only marginally so.

We have performed additional calculations for a ^{6}LiD reflector, exactly as for the other materials discussed in Ref. 2, and included the case $\alpha = 1.5 \times 10^{10}$ sec^{-1} to permit direct comparison with results quoted by Seifritz and Ligou.[1,3] The results are shown in Figs. 1 and 2. In addition to data given in Ref. 2, we have used $\rho = 2160$ g/cm^3 and $\rho E = 1.35\ P$ for ^{6}LiD at a pressure of 10^{18} dyn/cm^2

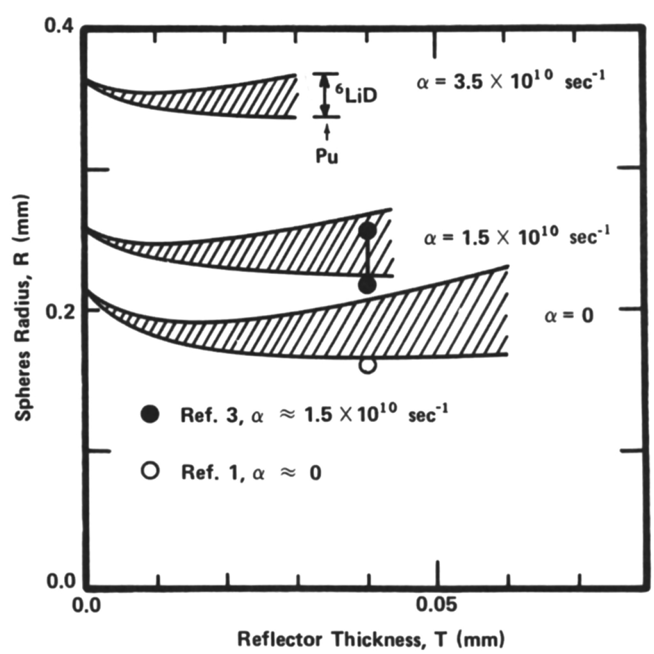

Fig. 1. Dimensions of ^{6}LiD-reflected spheres for various supercriticalities at 10^{18} dyn/cm^2.

[1]J. LIGOU and W. SEIFRITZ, *Nucl. Sci. Eng.*, **60**, 483 (1976).

[2]RANDALL K. COLE, Jr. and JAMES H. RENKEN, *Nucl. Sci. Eng.*, **58**, 345 (1975).

[3]W. SEIFRITZ and J. LIGOU, *Nucl. Sci. Eng.*, **56**, 301 (1975); also, *Trans. Am. Nucl. Soc.*, **18**, 18 (1974).

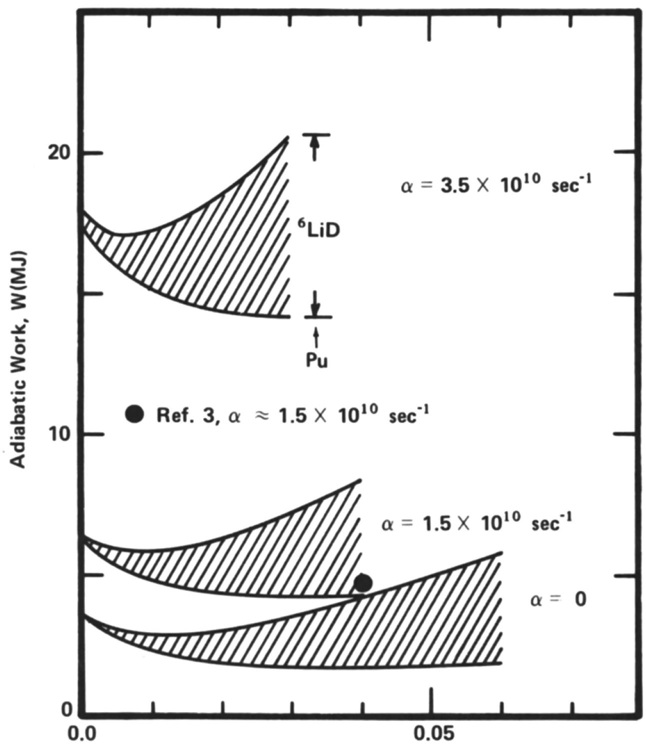

Fig. 2. Adiabatic work necessary to achieve various supercriticalities in ^{6}LiD-reflected ^{239}Pu spheres at 10^{18} dyn/cm^2.

(100 P Pa). The points given by Seifritz and Ligou fall very close to our curves (within 10%). Note that the work necessary to compress the ^{239}Pu to achieve $\alpha = 1.5 \times 10^{10}$ sec^{-1} (at a pressure of 10^{18} dyn/cm^2) is ~35% less with a 0.004-mm ^{6}LiD reflector than without, but, if the work necessary to compress the reflector is included, the total is almost 30% *greater*. For the optimum reflector, ~0.01 mm, the net savings is 10%—hardly enough to be significant. A greater difference, but only a factor of 3, results from the smaller α permissible with their enormously larger N_0.

Finally, we wish to comment on methods of calculating Rossi-α. The familiar kinetics relation,

$$\alpha = \rho/\Lambda \ ,$$

where $\rho = 1 - 1/k$ is the reactivity and Λ is the mean neutron generation time, must be used with great care for systems of this type. The full definitions of these quantities involve the flux-shape factor for the rapidly growing neutron population.[4] The conventional definitions result from the assumption that this is the same as the critical flux shape; their validity depends on the "time absorption," α/v, being negligible compared to other terms in the transport equation. As discussed in Sec. 1.5f of Ref. 4, large α favors high energy and hardens the spectrum. Thus, neutrons repeatedly scattered and slowed in a reflector such as DT simply lose importance (they cannot retard the growth), and Λ decreases toward the generation time for an unreflected pellet as α approaches the limiting value of 6.4×10^{10} sec^{-1} for infinite ^{239}Pu. Our numerical eigenvalue calculation is the only fully consistent method known to us for dealing with such highly supercritical systems. Our calculations for ^{6}LiD agree very well with those in Refs. 1 and 3 and are not very different from results for other reflecting materials given in Ref. 2. We believe, therefore, that the qualitative difference between ordinary and "absorbing" reflectors suggested by Ligou and Seifritz is not real, but rather represents the failure of the conventional kinetics equation for very high α in multiple-scattering materials.

[4]G. I. BELL and S. GLASSTONE, *Nuclear Reactor Theory*, Sec. 9.2b, Van Nostrand Reinhold Company, New York (1970).

Randall K. Cole, Jr.
Reactor Safety Studies Division

James H. Renken
Theoretical Division

Sandia Laboratories
Albuquerque, New Mexico 87115

March 23, 1976

Comments on "Analysis of the Microfission Reactor Concept"

I would like to comment on the criticism voiced by Winterberg[1] on the conclusions reached by Cole and Renken[2] concerning reflected pellets as fuel for "microfission" reactors. Our results,[3] using time-dependent S_n transport calculations, showed that fissionable pellets of ^{239}Pu and ^{235}U surrounded by deuterium shells "never attain high neutron multiplication rates due to the long transit times of the moderated neutrons."[3] More recent calculations have led to similar results for the transplutonium fissionable isotopes.

I have recently taken up Winterberg's suggestion[1] of assuming that the neutron thermal velocity in the reflector is characteristic of a hot plasma (~10 keV), and have run time-dependent transport problems with a neutron velocity of 1.4×10^8 cm/sec in the deuterium shell for all energy groups below ~10 keV in the 16-group Hansen-Roach cross-section set. This is admittedly an extreme case but one that should give an upper limit to the effect. The pertinent deuterium neutron cross sections in these lower energy

TABLE I

Time-Dependent Transport Results for Fissionable Microspheres of Maximum Theoretical Density

Pellet Composition	k_{eff}	Neutron Multiplication at 10^{-9} sec	Assumed Lowest Neutron Velocity in Reflector (cm/sec)
^{239}Pu	1.48	4.6×10^{28}	---
^{239}Pu + D	1.54	9.0	2.18×10^5
	1.54	5.0×10^5	1.4×10^8
	1.54	6.5×10^2	4.8×10^7
^{245}Cm	1.30	1.0×10^{44}	---
^{245}Cm + D	1.56	12.0	2.18×10^5
	1.56	3.0×10^6	1.4×10^8

[1]F. WINTERBERG, *Nucl. Sci. Eng.*, **59**, 68 (1976).
[2]RANDALL K. COLE, Jr. and JAMES H. RENKEN, *Nucl. Sci. Eng.*, **58**, 345 (1975).
[3]A.D. KRUMBEIN, *Trans. Am. Nucl. Soc.*, **18**, 19 (1974).