UCRL-ID-124782

General Parameter Study of a Bare, Cylindrical Reactor Having the Same Materials as Tory II-C

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

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MEMORANDUM - Naval Applications Memo Number 6.

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FROM: Theodore Stubbs

SUBJECT: General Parameter Study of a Bare, Cylindrical Reactor Having the Same Materials as TORY II-C.

Due to space and weight limitations aboard existing sea-going launch vehicles, it is of interest to study the properties of TORY II-C with the aims of reducing weight and size and increasing performance.

The one-dimensional neutronics code, ZOOM, has been used to obtain the dependence of the critical radius and mass of a bare, spherical reactor on the molar ratio of moderator to fuel. The materials used in the core are the same as are used in Tory II-C; the tie tubes of Rene' and Hasteloy having precisely the same molecular density as in Tory II-C, the moderator used is BeO, and the fuel is included as horseradish.* All of the materials are homogeneously smeared throughout the sphere and the Beo-fuel mixture is taken to have 40% porosity. (The Tory II-C core has an average porosity of about 52%). A temperature of 1500°K was assumed in the calculations.

Figure 1 is a graphic representation of the results of the above calculations. We define $\xi = \frac{\text{BeO}}{\text{horseradish}}$ molar ratio. For $\xi < 100$ and $\xi > 5{,}000$, we do not expect ZOOM to yield accurate results for at least two reasons. First, the energy-group scattering-transfer coefficients are flux-averaged over fluxes having an energy distribution expected in $200 \lesssim \xi \lesssim 3{,}000$; and second, the higher energy neutrons do not scatter isotropically in the center-of-mass system from all of the nuclear species present.

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* One mole of horseradish contains 1.066 moles of OyO_2, 1.000 mole of Y_2O_3, and 0.997 moles of ZrO_2.

[redacted]

Therefore, not only the transfer coefficients, but also the transport cross sections will suffer from this neglect in ZOOM. Thus, although we report results from $0 \leq \xi \leq 10^4$, the region of validity is expected to lie in $100 < \xi < 5{,}000$.

A shape-independent quantity which may be used to transform a spherical just-critical system to a just-critical system of any other geometry is the buckling.(1) For a given composition (ξ and porosity) all just-critical systems must have the same value of buckling. Figure 2 is a plot of buckling (B^2) vs ξ throughout the region of validity, as obtained in the above calculations from ZOOM.

Table I contains the information of both figure 1 and figure 2 in tabular form:

Table I

Critical Radius, Mass, and Buckling (B^2) as a Function of ξ as Given by ZOOM

ξ	Rc (cm)	Mc (Kg)	$B^2 \times 10^4 (cm^{-2})$
0.0	44.63	626.	44.1
0.5	44.45	592.	44.5
1.0	44.35	570.	44.7
5.0	44.97	438.	43.4
10.0	46.15	367.	41.5
50.0	50.5	161.0	34.92
100.0	52.04	96.9	33.10
500.0	57.03	27.6	27.80
1,000.0	62.7	18.6	23.20
5,000.0	102	15.8	9.03
10,000.0	~ 170	~ 37.3	~ 3.3

In particular, we would like to investigate the dependence of the critical mass of a Tory II-C - like bare cylinder upon diameter, length, composition, and porosity. If we define R_c = critical radius of a spherical system of given composition, r_c and L_c = critical radius and length, respectively, of a cylinder at the same composition, then we must have:

$$\left(\frac{\pi}{R_c + \Delta_c}\right)^2 = \left(\frac{\pi}{L_c + \Delta_L}\right)^2 + \left(\frac{2.405}{r_c + \Delta_r}\right)^2 . \qquad \text{(I)}$$

Here Δ is the extrapolation length associated with each geometry. Strictly speaking, Δ_R, Δ_L, and Δ_R are not precisely the same, however for systems in which $R > \Delta_R$, etc., it is valid to choose these quantities

$$\Delta_R = \Delta_L = \Delta_r = 0.71\ \lambda_{tr} \approx 2.7 \text{ cm}^{(2)}$$

The mass of fuel of any cylindrical system consisting of moderator and fuel is given by,

$$M = \frac{(1 - \Gamma)\ \rho^o_{mod}\ \frac{\pi}{4} d^2\ L}{\frac{\rho^o_{mod}}{\rho^o_{fuel}} + \frac{m_{mod}}{m_{fuel}}\ \xi}, \qquad \text{(II)}$$

where Γ = porosity

d = diameter of clyinder

L = length of cylinder

ρ^o = normal, solid density

m = molar weight.

It is seen from Figure 2 that for a given composition and density (ξ and Γ) there is a unique value of the buckling for a critical reactor. Combining equations I and II and information from Figure 2 we see that, in principle, it is possible to obtain a 3-dimensional graph of critical mass vs. L and d for a given value of Γ (ξ may be eliminated from the problem, if not analytically, then graphically). Figure 3 is just such a plot for Γ = 0.52. The variation of ξ is also plotted.

As stated before, Tory II-C has a value of $\Gamma \simeq 0.52$ and an equivalent buckling of $B^2 = 1.76 \times 10^{-3}\ cm^{-2}$. (2) If we assume that its equivalent bare cylinder is optimum, i.e. $L \simeq 0.935d$ (1) we may place this reactor on Figure 3 as shown. It should now be pointed out that the critical mass obtained in this manner differs from the actual value for two major reasons: The Tory II-C equivalent bare reactor is not precisely optimum and, most important, the fuel is only about 77% effective (2) due to the fact that it has a distribution in the core which is neither axially nor radially uniform.

It is also of interest to know how figure 3 transforms as a function of Γ. Given a critical core having a "solidity" of $(1 - \Gamma)$, we see that another core (primed system) of the same material composition (ξ is held constant) but at solidity $(1 - \Gamma')$ will be critical when all of its linear dimensions are transformed according to

$$X_j' = \left(\frac{1 - \Gamma}{1 - \Gamma'}\right) X_j \quad . \qquad \text{(IV)}$$

The transformation preserves the neutron escape probability and the number of neutron interaction mean free paths. Obviously, from equation (II) the critical mass must then transform according to:

$$M_c' = \left(\frac{1 - \Gamma}{1 - \Gamma'}\right)^2 M_c \ .$$

As an example, say we wish to know the values of the parameters which yield minimum critical mass for $(1 - \Gamma') = 0.6$. From figure 3, we obtain:

$$\xi' \simeq 2800 \simeq \xi$$

$$d' \simeq \frac{0.48}{0.6} \times 188 \simeq 150 \text{ cm}$$

$$L' \quad \frac{0.48}{0.6} \times 175 \simeq 140 \text{ cm}$$

$$M_c' \quad \left(\frac{0.48}{0.6}\right)^2 \times 24.5 \simeq 15.7 \text{ Kg}$$

Finally, a departure from a uniform distribution will result in a change in the amount of fuel required to make a reactor of a given size critical. As pointed out by Goldberg and Reynolds [2], the "fuel worth" for non-uniform loading may be obtained by averaging the loading distribution over the square of the spacial neutron flux distribution. Since we demand that the porosity and physical dimensions remain constant, equation (II) shows how M_c and ξ must be varied.

It must be stated that Figure 3 is not to be taken as gospel. It is intended that this give only a reasonable approximation to the behavior of a cylindrical reactor having the same constituents as TORY II-C. Indeed the example at the bottom of the previous page is not precisely consistent with equation (II) as can easily be verified.

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(1) Glasstone and Edlund "The Elements of Nuclear Reactor Theory" Van Nostrand (1954).

(2) E. Goldberg and H. L. Reynolds. TORY II-C Memorandum No. 350 July 5, 1962.

FIGURE 1.

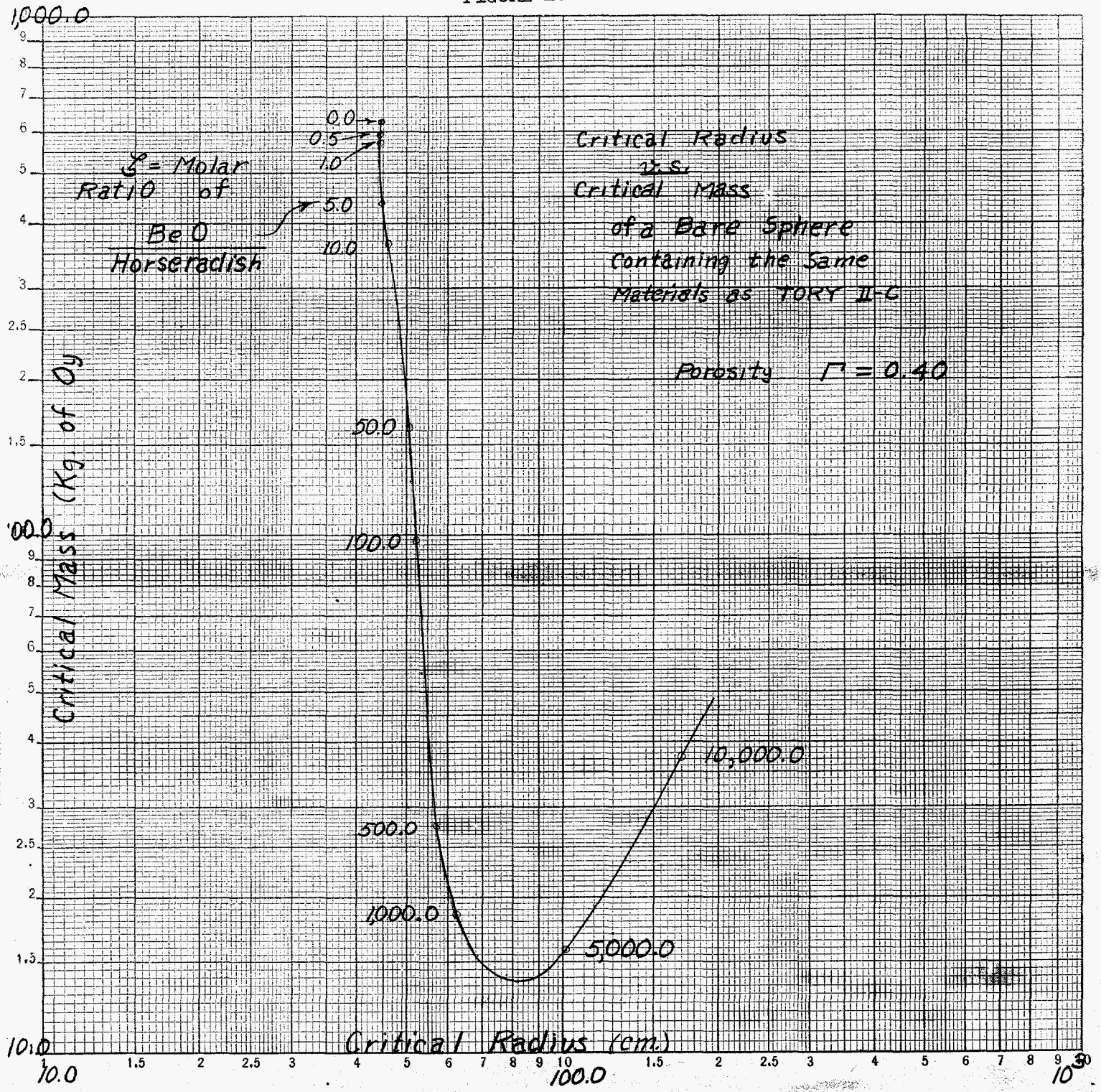

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FIGURE 2.

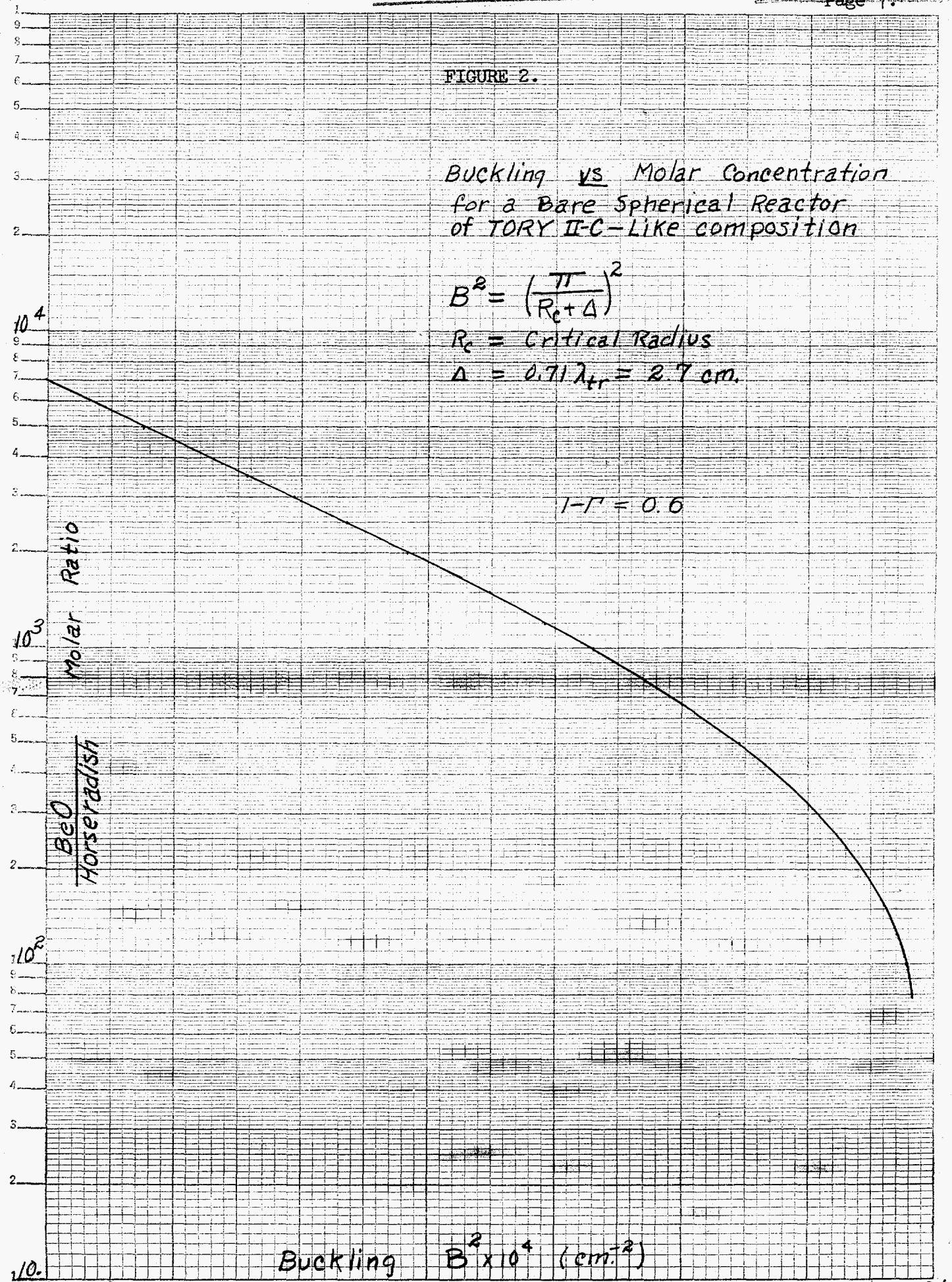
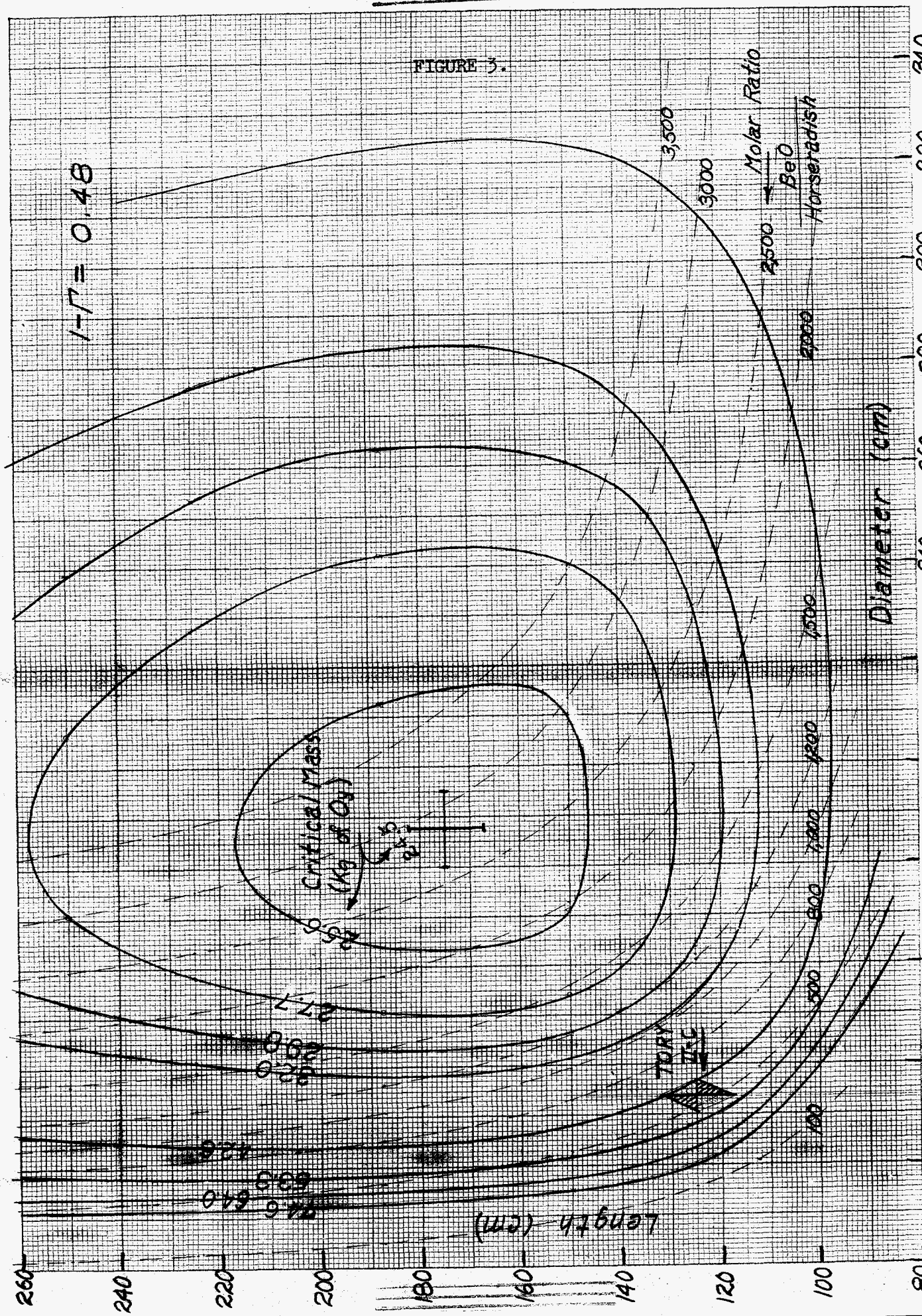

Buckling vs Molar Concentration
for a Bare Spherical Reactor
of TORY II-C-Like composition
$B^2 = \left(\frac{\pi}{R_c + \Delta}\right)^2$
R_c = Critical Radius
$\Delta = 0.71\,\lambda_{tr} = 2.7$ cm.
$1-\Gamma = 0.6$
Molar Ratio
BeO / Horseradish
Buckling $B^2 \times 10^4$ (cm^{-2})
10^4
10^3
10^2
10.
6.
8
10
12
14
16
18
20
22
24
26
28
30
32
34

FIGURE 3.



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