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EXTENDED SUBCRITICAL LIMITS FOR SLIGHTY ENRICHED UO2 (≤ 5 WT % U-235)

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0. INTRODUCTION

The Nuclear Criticality Safety (NCS) of most processing operation may be establised using the suitable maximun permisible values (MPV) for simple systems.

The regulations of NCS (ref.1) do not define strict rules to stablish these MPVs, but they indicate that the values of the parameters ("Subcritical limits"), must be reduced to an amount that quite enough assures the subcriticality.

At ENUSA's Juzbado Fuel Fabrication Plant (SPAIN) we have been using a conservative criterion, defining the MPV as the parameter values which can lead to a K-eff of 0.95 at top. The MPVs are calculated for very restrictive conditions and, on many occasions, when analising a specific plant is convenient to use criterion for increasing this MPV.

In this paper we describe the method used to calculate MPVs and the way to increase this. The results are represented in tables and figures of very easy use.

In all cases we suppose mixture UO_2-H_2O enriched 5 wt% ^{235}U.

1. GENERAL DESCRIPTION OF THE METHOD

The method used to determine the MPVs is the one that follows:

1º. Find the minimum critical values of the parameters using the data of the ref. 2 and 3.

2º. Obtain, using again the ref. 2 and 3 , M^2, δ and K_∞.

3º. Using the ecs 1, 2, 3 and 4 find the parameters that corresponds to K-eff =0.95. In all cases we suppose optimum moderation and full reflection.

The obtained results can be seen in table 1. The detailed calculations are described in the 2-nd section.

TABLE 1

MPV OF MIXTURE (UO_2 + H_2O)

MPV	HOMOGENEUS	HETEROGENEUS
- MASS	31 Kg. UO_2	25 Kg. UO_2
- VOLUME	19,5 Liters	16 Liters
- RATIO OF INFINITE CYLINDER	11.2 cm.	10.4 cm.
- THICKNESS OF INFINITE SLAB	10.25 cm.	8.9 cm.

a) Sphere

$$(1)\quad Bg^2\ (\text{sphere}) = \frac{\pi^2}{(R_s + \delta_s)^2}$$

b) Cylinder of finite length

$$(2)\quad Bg^2\ (\text{cylinder}) = \frac{(2.405)^2}{(R_c + \delta_c)^2} + \frac{\pi^2}{(H+2\delta_c)^2}$$

c) Slab with finite dimensions

(3) $$Bg^2 \text{ (slab)} = \frac{\Pi^2}{(T+2\delta_t)^2} + \frac{\Pi^2}{(L+2\delta_t)^2} + \frac{\Pi^2}{(W+2\delta_t)^2}$$

d) General geometric buckling

(4) $$Bg^2 = \frac{K_\infty - K_{ef}}{K_{ef} M^2}$$

Where:

R_s = Radius of a sphere
T = Finite slab thickness
L = Finite slab length
W = Finite slab width
H = Finite cylinder height
δ_s = Extrapolation distance of a full reflected sphere
δ_t = The same for a slab
δ_c = The same for a cylinder
M^2 = Migration area
Kef= We always choose 0.95 as a criterius to establish MPV

Besides we have increased theses values limiting some additional parameters such as: relationship H/U, slab length, slab width, cylinder height. The results are shown in figs. 1 to 6. The detailed calculations are discribed in 3-rd section.

We have verified the methods above mentioned making some additional calculations with the Scale System. They prove the validity of the used method

2. THE PROCESS TO STABLISH MAXIMUN PERMISIBLE VALUES (MPV)

2.1. MPV FOR HOMOGENEUS SYSTEMS

a) MPV for Mass

Using tables of ref. 2, we obtain a density, d, 1.000 g. U/liter for minimun critical mass and for this density and full reflection, we find:

- $K_\infty = 1.39$
- $M^2 = 28.5\ cm^{-2}$ and
- $\delta_s = 6\ cm$

Of ecs (4) and (1) we obtain;

$$R_s = \frac{\pi}{\{(1.39-0.95)/\ (0.95 \cdot 28.5)\}^{1/2}} - 6 = 18.65\ cm$$

So,

$$\text{MPV for mass} = \frac{4\pi}{3}\ 18.64^3\ cc.1g\ U/cc = 27,14\ g\ U = 31\ Kg\ UO_2$$

b) MPV for volume

Using ref. 2 and ecs 1 and 4 we find:

- Minimun critical radius = 18.41 cm
- $d = 2100\ g\ U/1$
- $K_\infty = 1.44$
- $M^2 = 28\ cm^{-2}$
- $\delta = 6.45\ cm$

$$R = \frac{\pi}{\{(1.44-0.95)/\ 0.95x28\}^{1/2}} - 6.45 = 16.7\ cm$$

$$V = 4/3\pi\ \ R^3 = 19,756\ cc = 19.75\ liters$$

c) <u>MPV for infinite cylinder</u>

Using tables of ref. 2, we obtain a density, d, 2.100 g U/l for minimum radius infinite cylinder and full reflection, we ind:

- K_∞ = 1,44
- M^2 = 28 cm^{-2}
- δ = 6.45 cm

of ecs (2) and (4) results

$$R_c = \frac{2.405}{\{(1.44-0.95)/\ 0.95x28\}^{1/2}} - 6.45 = 11.2 \text{ cm}$$

d) <u>MPV for a infinite slab</u>

The density for a minimum critical slab is 2.100 g. U/l (ref. 2). For this density,

- K_∞ = 1.44
- M^2 = 28 cm^{-2}
- δ = 6.45 cm

of ecs (3) and (4) we obtain,

$$L= \frac{\pi^2}{\{(1.44-0.95)/(0.95x28)\}^{1/2}} - 2 \times 6.45= 10.25 \text{ cm}$$

2.2. MPV FOR HETEROGENEUS SYSTEMS

Following the same method but using the tables of ref.3 for heterogeneus system we obtain these MPVs.

a) <u>MPV for mass</u>

- Minimum critical mass: 1560 g. ^{235}U
- Rods diameter: 0.254 cm
- M^2 = 29.77 CM^{-2}
- δ = 6.29 cm
- d (^{235}U)= 47.32 g. $^{235}U/l$

- The sphere volume for minimun critical mass:

$$Vc = \frac{\text{minimum critical mass } ^{235}U}{\text{density } ^{235}U} = \frac{1560}{47.32} = 32.97 \text{ liters}$$

- The sphere radius for minimum critical mass:

$$R_c = \left(\frac{3 V_c}{4}\right)^{1/3} = 19.89 \text{ cm}$$

With these parameters and using ecs (1) and (4) for Kef= 1

$$K_\infty = 1 + \frac{29.77 \quad \pi^2}{(19.89 + 6.29)^2} = 1.43$$

if Keff: 0.95

$$R = \frac{\pi}{\{(1.43-0.95)/ 1.43x29.77\}^{1/2}} - 6.29 = 17.86$$

$$\text{MPV for Mass} = \frac{4\pi}{3} (17,86)^3 47.32 = 1.128 \text{ g.}^{235}U = 22 \text{ kg.U} =$$

$= 25$ kg UO_2 .

b) **MPV for volume**

- Minimum critical volume= 22.1 l.
- Rods Diameter = 0.762 cm
- M^2 = 30.15 cm^{-2}
- δ = 6.57 cm
- d (^{235}U) = 118.56 g ^{235}U/liters

Substituting these values in the ecs (1) and (4). for Kef = 1

$$K_\infty = 1 + \frac{M^2 \pi^2}{(R_c + 6.29)^2} = 1 + \frac{M^2 \pi^2}{\{(\frac{3x22.1}{4})^{1/3} + 6.29\}^2} = 1.518$$

if Keff: 0.95

$$R = \frac{\pi}{\{(1.518 - 0.95)/0.95\ 30.15\}^{1/2}} - 6.57 = 15.75$$

$$\text{MPV for Volume} = \frac{4\pi}{3}\ 15.75^3 \approx 16\ \text{l.}$$

c) **MPV for infinite cylinder**

- Minimun critical radius = 17,7 cm
- Rods Diameter = 0.762 cm
- M^2 = 30.15 cm^{-2}
- d (^{235}U)= 118.56 g. ^{235}U/liter
- δ = 6.63 cm

sustituting in ecs (1) and (3) for Kef = 1

$$K_\infty = 1 + \frac{M^2\ 2.405^2}{(Rc + \delta)^2} = 1.519 \quad K_\infty = 1 + \frac{30,15 \cdot 2,405^2}{(11,7 + 6,63)}$$

If Keff. = 0,95

Rc= [2,40/{(1,519 - 0,95)/0,95 · 30,15}] - 6,63 ≈ 10,4 cm

d) <u>MPV for slab</u>

- hc (minimum critical thickness) = 10,6 cm
- rods diameter = 0.762 cm
- M^2 = 30.41 cm^2
- δ = 6.63 cm
- d = 135.57 g. ^{235}U/liter

sustituting in ecs (3) and (4) for Keff = 1

$K_\infty = 1 + [30,41\ \pi^2 / (10,6 + 2 \cdot 6 \cdot 63)^2] \approx 1,51$

If Keff. = 0.95

VMP for thickness =

$= [\pi/[(1,51 - 0,95)/0,95 \cdot 30,41]^{1/2}] - 2 \times 6.83 \approx 8,9$ cm

3. CRITERIA FOR INCREASING VMP

A way to increase MPV is limiting the degree of moderation of material. (relationship H/U). In other cases MPVs can be increased limiting one dimension in the geometry instead of considering it infinite.

3.1. INCREASED VMP AS FUNCTION OF RELATIONSHIP H/U FOR HOMOGENEUS SYSTEMS

In the case of homogeneus system the reactivity of the material is determined by the relationship between H/U. If we are sure that in an homogeneus unit the relationship H/U has a certain maximum value, we can use it to increase the MPV. Of course this is only possible when that relationship H/U has already been determined by analysis and there is a moderated strict control. We have been calculating this taking as a starting the data in the Ref. 2, and representing the results in Fig. 1 and 2.

We have estimated, for an homogeneous system the maximum relationship H/U for a determined density UO_2, that is

$$VF(UO_2) + VF(H_2O) = 1$$

VF = Volume fraction

For these relationships H/U we have calculated the values of a mass, volume, diameter of cylinder and thickness slab.

The ratio H/U is calculated as follows

$$H/U = \frac{\left[1 - \{p(U) \cdot \frac{Pmol\ UO_2}{Pmol\ U \cdot TD(UO_2)\}}\right] \cdot 2}{Pmol\ H_2O} \div \frac{d(U)}{Pmol\ U} - 1] =$$

$$2.74 \left[\frac{9.66}{d(U)} - 1\right]$$

Where we have sustituted the following values:

VF = Volume fraction
d(U) = density of uranium = g de U/cc
Pmol U ≈ 238
Pmol UO_2 ≈ 270
Pmol H_2O ≈18
TD(UO_2) = teorical density UO_2 = 10.96 g/cc

Now we make the calculation according to the method described above. The results are represented in figures 1 and 2. We have obtained the values K_{∞} and M^2 for the differents ratio H/U from ref. 2.

a) Safe batch (kg) as funtion as ratio H/U (fig. 1)

$$M = \frac{4\pi}{3}\, d \left[\frac{\pi^2}{\{(K_{\infty}-0.95)/0.95\ M^2\}^{1/2}} - \delta\right]^3$$

b) Volume (l) safe as funtion as ratio H/U (fig. 1)

Using ecs (1) and (4) we obtain

$$V = \frac{4\pi}{3} \left[\left(\frac{\pi}{\{(K_{\infty}-0.95)/0.95\ M^2\}^{1/2}}\right) - \delta\right]^3$$

c) Infinite cylinder safe radius (cm) as function as ratio H/U (fig. 2)

Using ecs (2) and (4) we obtain

$$R = \frac{2.405}{\{(K_\infty - 0.95)/0.95\ M^2\}^{1/2}} - \delta$$

d) Slab safe thickness (cm) as function as ratio H/U (fig. 2)

$$T = \frac{\pi}{\{(K_\infty - 0,95)/0,95\ M^2\}^{1/2}} - 2\ \delta$$

e) Maximun admissible H/U in moderated control area

A good parameter for criticality control is the limitation of ratio H/U. We have fixed the maximum admissible relationship H/U in the fisil material. To determine this H/U we have estimated, using SCALE, the K - ∞ for different mixtures of UO_2 - H_2O until we have found an K-infinite = 1. This value is H/U = 0.46 and it can be taken as the maximum admisible H/U in moderated control area. Also we have calculated the radius of spheres full refleted by water with different densities of uranium for H/U = 0,46 and Keff = 0,95. The results are shown in fig 3. The moderation control must be completed by stablishing a limit for the amount of H which due to a mistake can be incorporated in the material. To prevent this effect we suppose a small sphere UO_2 - H_2O with the most reactive composition (1) with a relationship H/U = 0.46 to inmerse in a infinite medium We have been increasing the radius of inner sphere up to Keff = 0,95 (fig 4). This value is 16 liters. Its the limits of H_2O or equivalent moderator admited in an area with moderation control.

(1) 2.27 g UO_2/cc and 0.793 g H_2O/cc

It's the limit of H_2O or equivalent moderator admited in an area inder moderation control.

3.2. INCREASING MPV FOR ACUMULATION RODS

This way of increasing the value of MPV can also be used with heterogeneous systems, although in this case the calculation is more complicated. The sequence of XSRNDRNPN-KENO IV of code SCALE has been used to increase the slab thickness for heterogeneous materials. In this way we have calculated the most reactive array rods. However in the instalations most of the accumulation rods are compact. That means they are in contact one another and even in a case of flooding the systems are in the submoderated region. Using the most reactive type of rods of our plant and supposing them to be in contact forming a squarepitch, which is more reactive than the triangular picht. We have done several calculations XSRDRNPN-KENO IV for different thickness of an infinite slab of compact rods full reflected and flooded. The thickness that gives as a result a K-eff ≤ 0.95 (including the uncertainly) is of 23.3 cm, so for acumulations of this type the general MPV, 8.9 can be increased in more than the double.

3.3. INCREASING MPV FOR FINITE GEOMETRY

To increase MPVs we must bear in mind that the units are finite of limited dimensions. In fact the K-eff can be written.

$$K\text{-eff} = \frac{K_\infty}{1 + M^2 \ Bg^2}$$

Where K_∞ and M^2 depend on the characteristics of the material and Bg^2 depends on geometry and shightly on the material.

a) Cylinder infinite

In the case of a finite cylinder with radius and length L: $Bg^2 = Bg^2$ (r, L, δ). The Bg^2 of an infinite cylinder with the maximun permissible radius, r_m, is Bg^2 (r_m, ∞, δ) From the ecuation (1),

Bg^2 (r, 1, δ)= Bg^2 (r_m, ∞, δ)

You can find in fig. 5 a funtion r=r (L)

b) Slab finite

In a similar way you can find the maximun permissible thickness of a slab a sides X and Y,

Bg^2 (X,Y,Z)= Bg^2(X, ∞, ∞, δ)

from Ec.(2)

$$h_F = \frac{A}{B} - 2\,\delta \text{ where,}$$

$$A= (h_I + 2\,\delta)\ (X + 2\,\delta)\ (Y + 2\,\delta)$$

$$B= \{(X+2\delta)^2 (y+2\,\delta)^2 - (h_I + 2\delta)^2\ (y+2\delta)^2 - (h_I + 2\delta)^2 (x+2\delta)^2\}^{1/2}$$

The results are shown in fig. 6 and 7.

4. SUMMARY

There is not a precise criteria to obtain the MPVs. We have choosen a method which makes K-eff = 0.95 in the ecuation

$$K\text{-eff} = \frac{K_\infty}{1 + M^2 Bq^2}$$

The MPVs are usually used for very restrictive conditions which make more difficult their use. We have seen that taking into account finite units or limiting the relation H/U, less restrictive MPV can be defined, allowing a wider range usage.

The results are represented in table and figures.

5. REFERENCES

1. "Nuclear Safety Guide" TID 7016, Rev. 2, 1978

2. ARH-600. R.D. Carter, G.R. Kile, K.R. Ridgway, 1968.

3. DP-1014, "Critical and safe masses and dimensions of lattice of U and UO_2 rods in water", H.K. Clark, 1966.

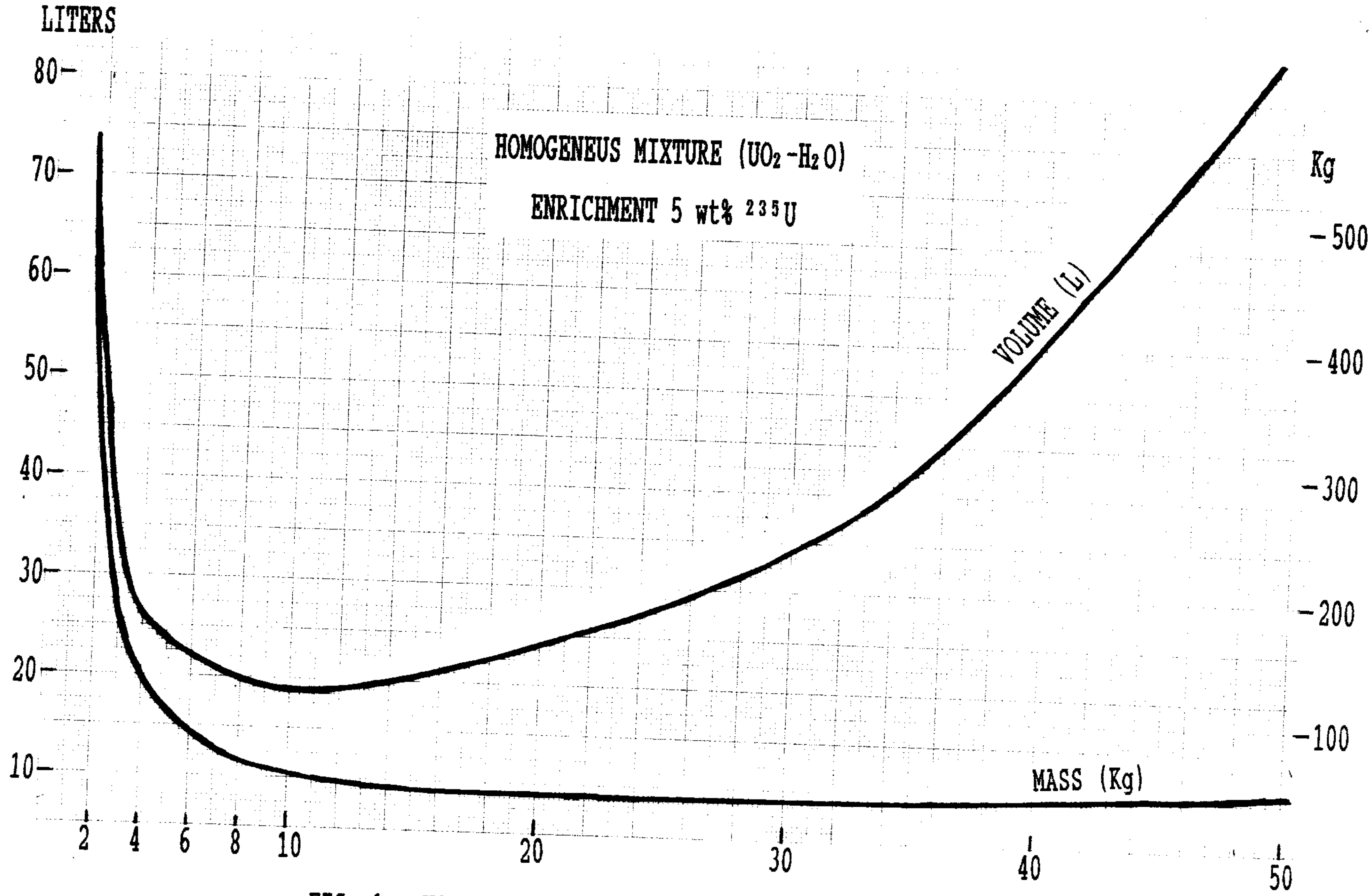


FIG. 1 VOLUME AND SAFE MASS AS A FUNTION H/U ATOM RATIO

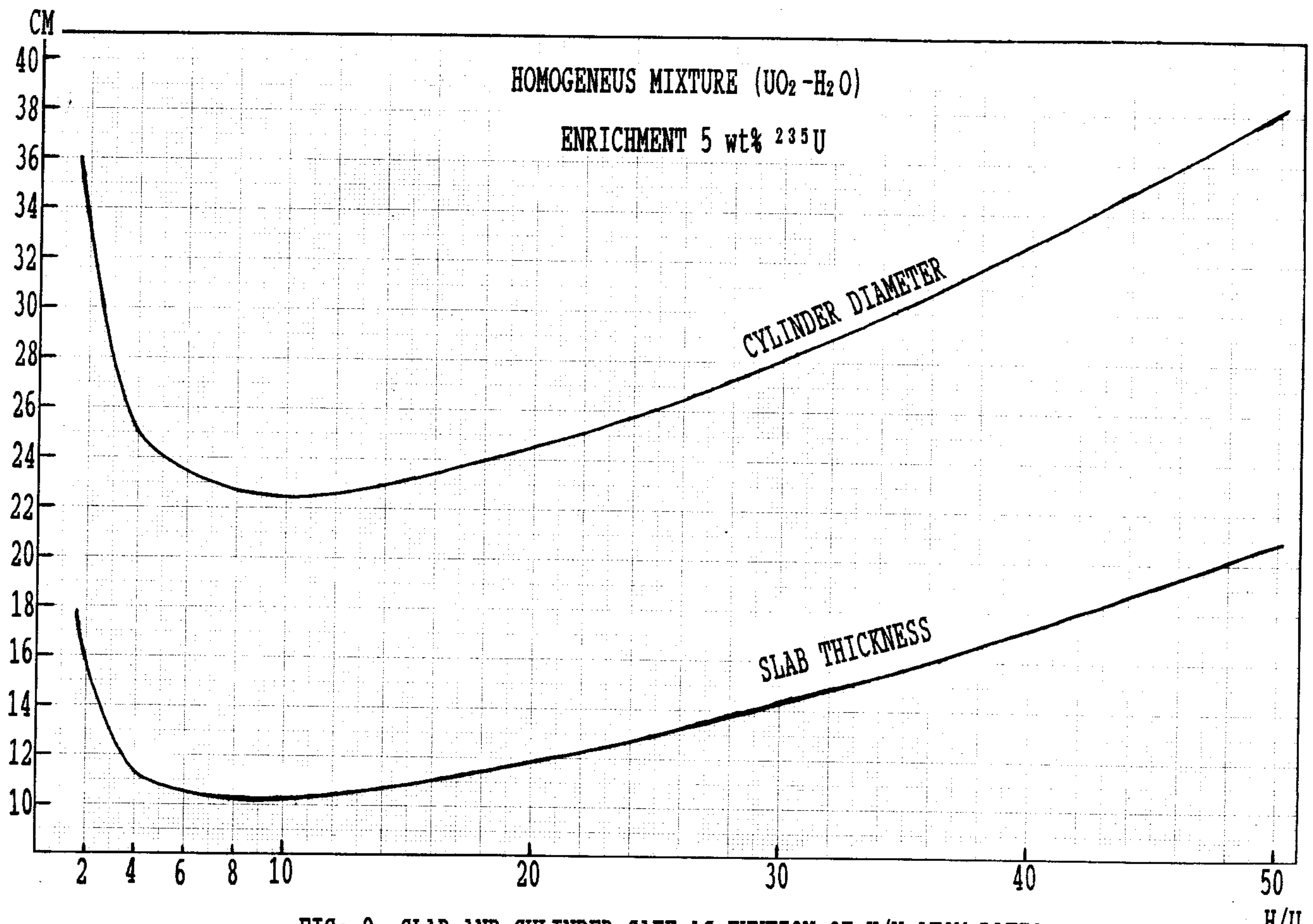


FIG: 2 SLAB AND CYLINDER SAFE AS FUNTION OF H/U ATOM RATIO

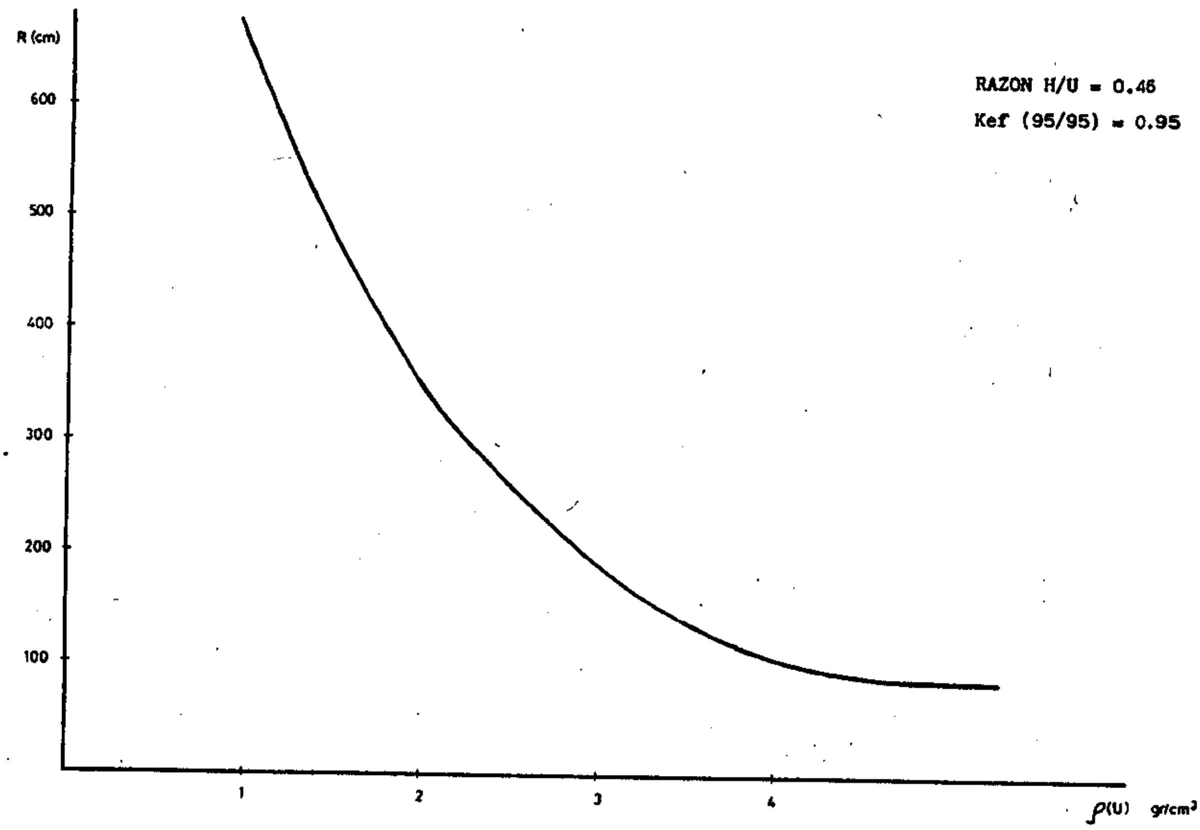
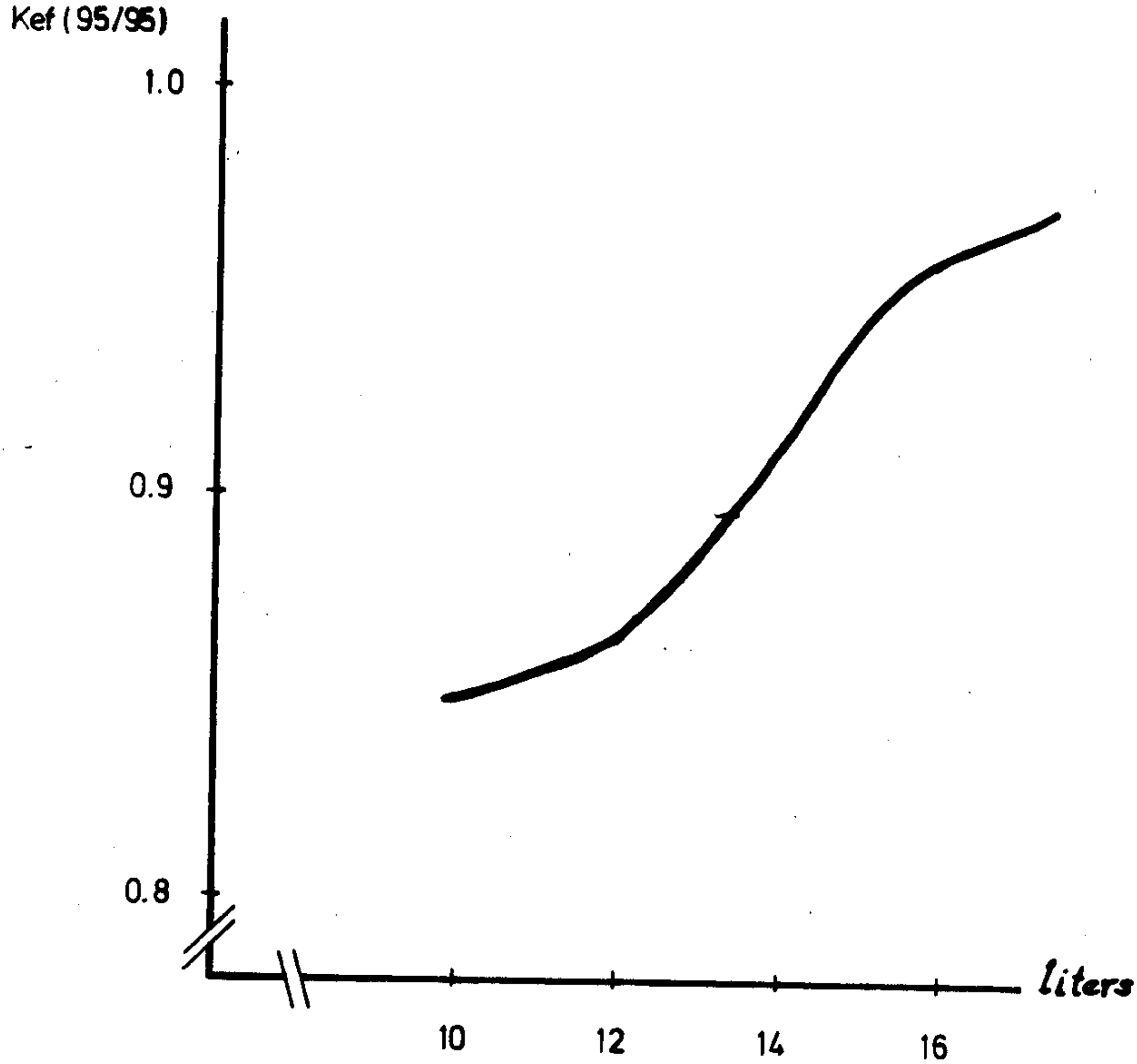


FIG. 3 RADIUS OF FULL REFLETED
SPHERE AS FUNTION OF DENSITY



Kef as function of H_2O liters in most reactive inner sphere of an infinitum medium (UO_2, H/U = 0.46)

FIG. 4

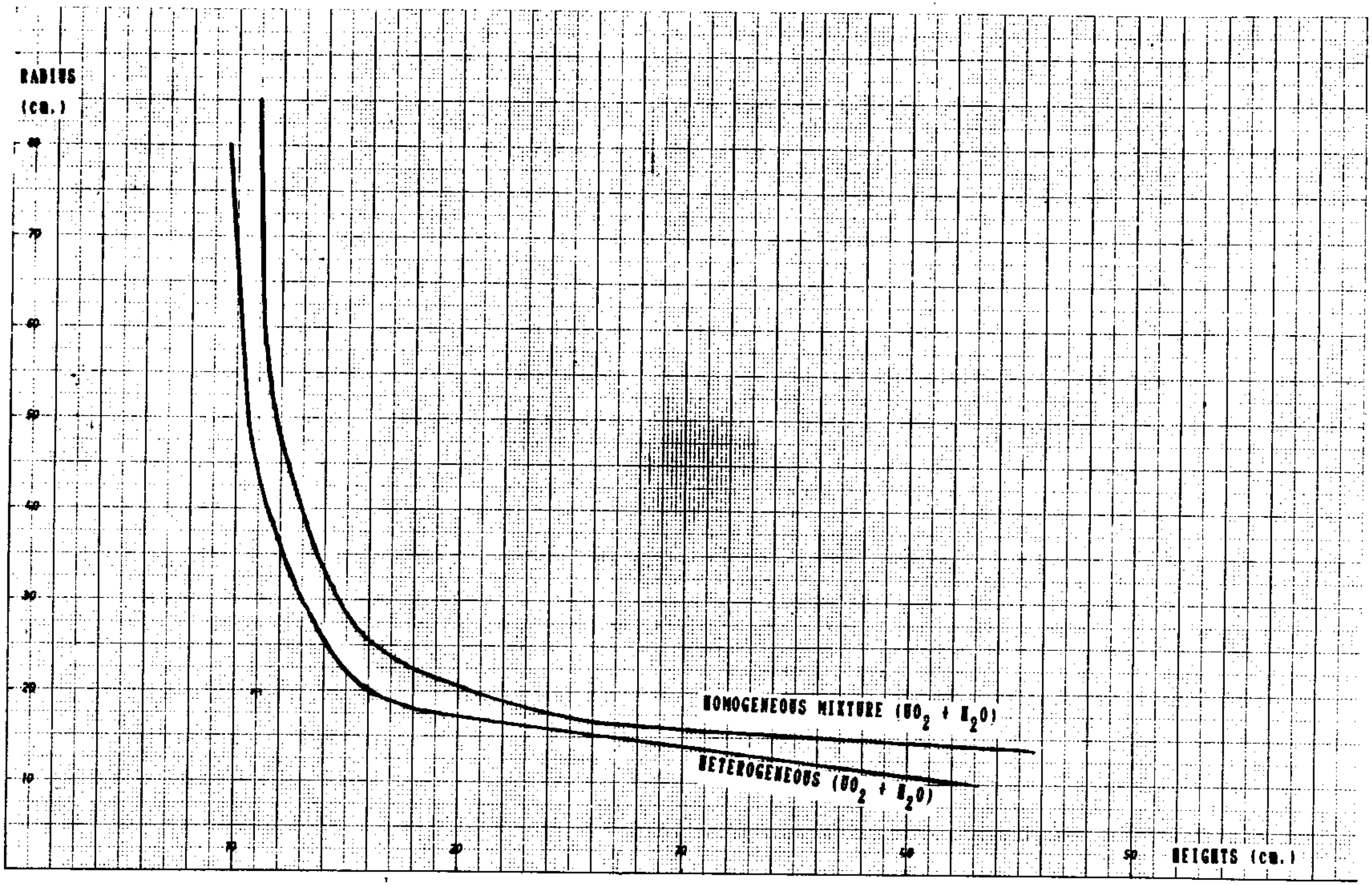


FIG. 5. CYLINDER SAFE (Kef ≤ 0.95) AS FUNTION OF RADIUS AND HEIGHT. ENRICHMENT 5% WT ^{235}U

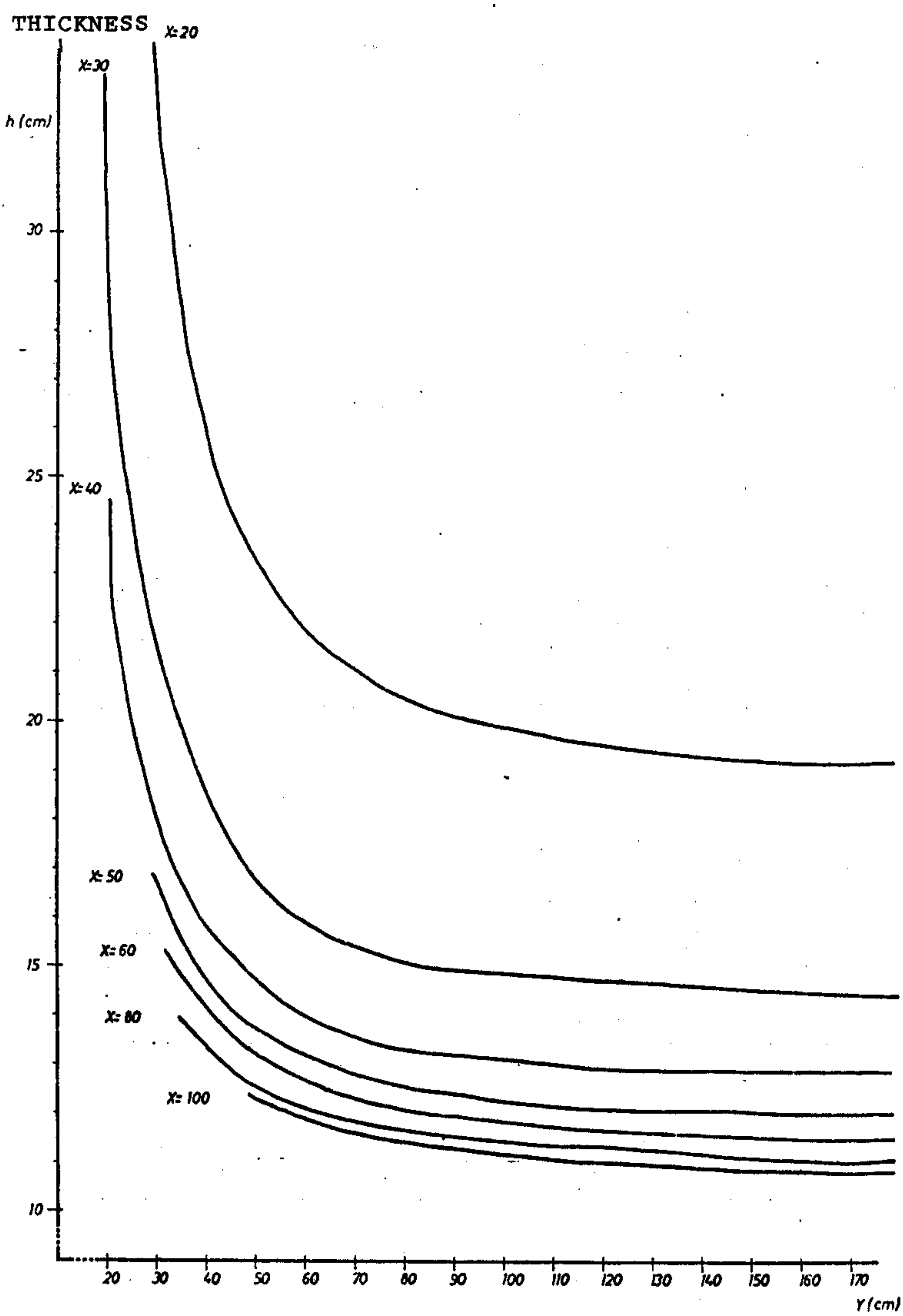


FIG. 6 SLAB THICKNESS AS FUNTION OF BASE DIMENSION FOR HOMOGENEUS SYSTEM

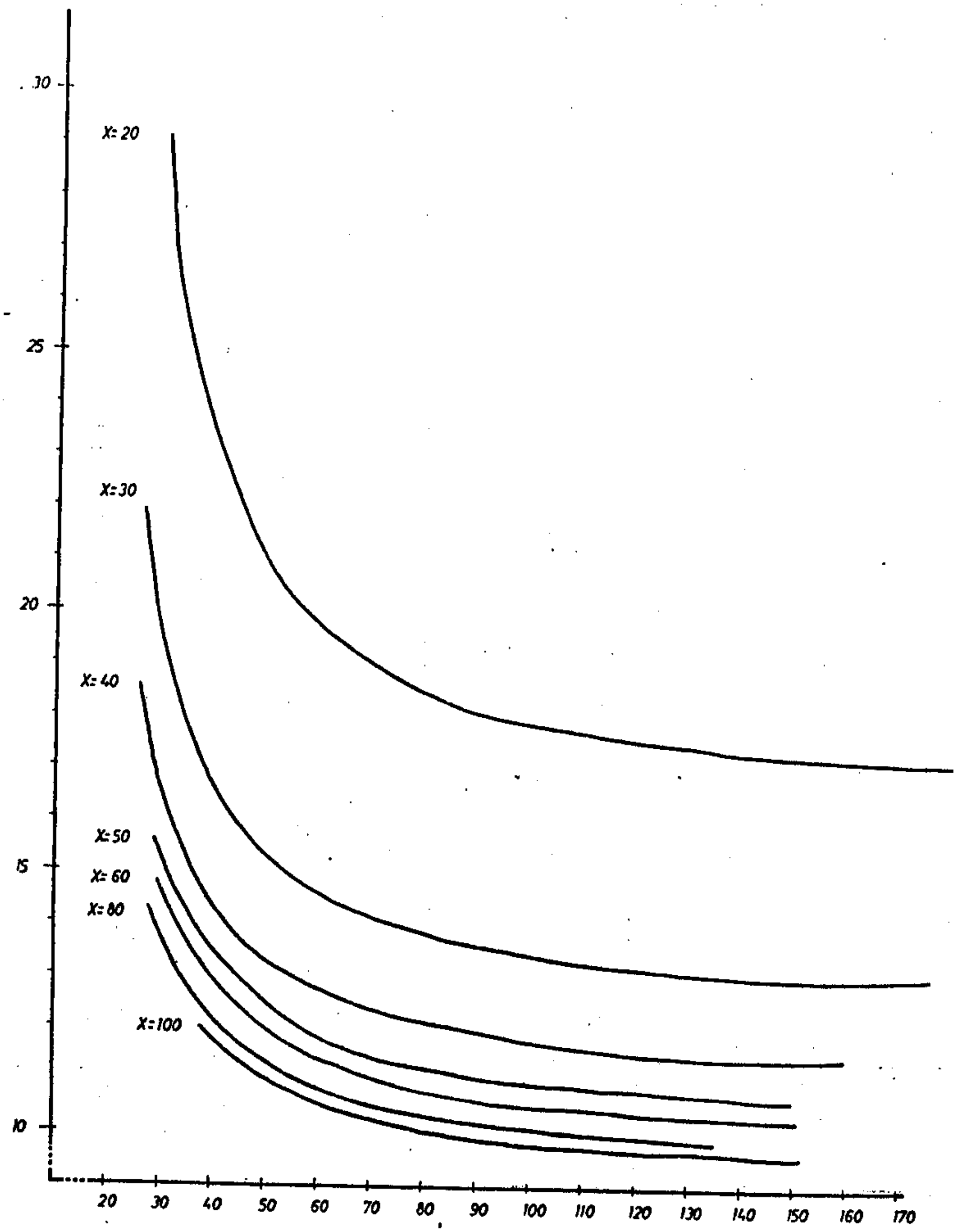


FIG. 7 SLAB THICKNESS AS FUNTION OF BASE DIMENSION FOR HETEROGENEUS SYSTEM