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The Design and Construction of a D_2O-Moderated ^{252}Cf Source for Calibrating Neutron Personnel Dosimeters Used at Nuclear Power Reactors

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

An ideal neutron dosimeter would be one whose response (i.e., reading per unit fluence) matches, as a function of neutron energy, the quantity, dose equivalent per unit fluence. Such a dosimeter would be "ideal" in the sense that its reading per unit dose equivalent would be independent of neutron energy. Since practical dosimeters currently available are far from ideal, one must be careful to choose a dosimeter which has an adequate response in the spectrum of interest, and to calibrate this dosimeter in a spectrum which is either similar to that of the environment of interest, or at least gives a similar calibration factor.

It has been general practice to calibrate neutron dosimeters and remmeters using bare fission or (α,n) neutron sources, such as Pu-Be. (An exception to this general rule is the Lawrence Livermore Laboratory [1], where moderated sources are also used for calibration.) This practice has been carried over to the NRC pilot program for testing the performance of the suppliers of personnel-monitoring services, which uses a bare ^{252}Cf source. While this set-up approximates an ideal point source with a well-known spectrum, it is recognized that the ^{252}Cf fission spectrum is not a realistic representation of the spectra encountered in the vicinity of a reactor, since spectra outside reactor pressure vessels are much softer than those from ^{252}Cf (or Pu-Be) sources. (Figure 1[1] shows the neutron spectrum from ^{252}Cf [2]; Fig. 2 shows the spectrum at the Alabama Power and Light Company's Farley Nuclear Plant, as determined by Bonner Sphere measurements [3].)

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[1] In the figures in this paper, the word "flux", which is commonly used in reactor applications, is used for "flux density" (or fluence rate), the term usually used in radiation protection applications.

The problems that can arise when the test spectrum, the spectrum of practical interest, and the dosimeter response function do not match can be inferred from Figs. 1 and 2. The albedo dosimeter response per unit fluence (shown in Fig. 1) is adequate over much of the energy range of interest covered by the spectrum at the Farley Nuclear Plant (Fig. 2). Only the high energy "tail" of the response function, however, overlaps the californium spectrum (Fig. 1). Thus, testing an albedo dosimeter processor's performance with a bare californium source does not necessarily constitute a good test of his performance in the (softer) spectra of practical interest. It is thus highly desirable to develop a calibration test source whose spectrum is more nearly like the spectra found outside reactor pressure vessels. Such a source would be particularly important for any future mandatory tests of processors who provide neutron dosimetry services for nuclear power reactors.

OBJECTIVES OF DEVELOPING A MODERATED NEUTRON SOURCE

A major goal of this project was to develop a moderated neutron source whose spectrum simulates the neutron spectrum found in the vicinity of a power reactor. Such a source would be used for testing processor performance, as well as for calibrating dosimeters and remmeters.

R. V. Griffith and co-workers at LLL have systematically characterized many moderated sources [1]; some of the calculations to be discussed here follow along the same general lines. We will, however, be specifically concerned with matching the test spectrum with both the dosimeter response function and the "real spectrum", i.e., the spectrum found inside the containment shell of a typical nuclear power reactor.

PROPOSED MODEL NEUTRON SPECTRA

The neutron spectrum we chose to use as a model for the development of a moderated Cf source was one of the spectra measured at the Alabama Power and Light Company, Farley Nuclear Plant. The Farley plant was chosen as the model since an extensive series of well-documented measurements at this reactor were previously made by Hankins and Griffith from LLL [3] and by Butler, Ohnesonge, and Auxier from ORNL [4]. Although neutron spectra measurements have since been made at a number of other reactors, it is felt that the spectra found at the Farley plant typified these other spectra and could be appropriately used as the model spectra. Since Hankins and Griffith [3] concluded that "no significant variations in the neutron spectrum existed at 27 different survey points" where the spectra were measured, we felt justified in using only one set of the Hankins and Griffith spectral data as representative of the entire set.

To explore the range of parameters which may be encountered we also considered a calculated spectrum for the Arkansas Power and Light reactor [5]. This is a spectrum calculated for the mid-cavity radius, at the core mid-plane elevation. This spectrum will be much harder than the measured spectrum at the Alabama Power and Light plant, since it has a component of neutrons coming directly through the pressure vessel, unmoderated by any scattering in concrete. The Arkansas spectrum does represent a realistic spectrum, however, since there are isolated areas in many reactors where personnel can be exposed to neutrons coming directly from the pressure vessel with little further moderation [6]. Hence, we concluded that the measured spectra at Alabama Power and Light and the calculated spectrum at Arkansas Power and Light represented a reasonable absolute range of spectra likely to be encountered.

The Bonner sphere measurements [3] made at the Farley plant, as do all Bonner sphere measurements, show no detailed structure in the spectrum. To help understand the physics of the situation, we initially worked with the above mentioned calculated spectrum, as well as with the calculated water-moderated iron-shielded spectra given by Ing and Makra [7]. We also studied several of the other spectra in the Ing and Makra Compendium, and used their calculated light and heavy water moderated spectra as input for some of our calculations.

We found that it was not practical to reproduce the actual differential leakage spectrum in fine detail. For example, calculations show that one of the prominent features of a typical reactor neutron spectrum is a high, narrow peak at ~ 24 keV, arising from the well known "window" in iron. The only way that this feature can be reproduced in a moderating assembly is by use of iron in the moderator, but this would require at least several hundred pounds of iron, and would still not yield the large low energy flux which was seen at the Farley plant. It was felt that rather than attempt to duplicate accurately a detailed differential spectrum, it would be appropriate to develop a simulation source whose neutron spectrum would yield similar integral responses when measured by dosimeters and neutron survey instruments such as an albedo dosimeter or the 9-inch-sphere remmeter.

CALCULATED NEUTRON DOSIMETER AND SURVEY INSTRUMENT RESPONSE TO NEUTRON SPECTRA

For each spectrum of interest, we calculated the following instrument responses per unit fluence: 1) a typical albedo dosimeter [8], since this dosimeter is frequently used at nuclear reactor sites and is probably the most appropriate one now available; 2) the Eberline 9-inch sphere remmeter, which seems to be the most commonly used remmeter at reactors; 3) a 3-inch sphere, and the 9"/3" ratio, since this ratio can be used to characterize a neutron spectrum [3,8]; and, 4) a Bonner Sphere spectrometer set [9].

In addition to these instrument responses, we also calculated the dose equivalent per unit fluence [8] for each of the spectra. The results of these calculations for everything but the Bonner spheres are listed in Table I. The Bonner sphere calculations are plotted in Fig. 3.

Before discussing the numbers themselves, it is interesting to try to understand, qualitatively, the nature of the various response functions.

A. Dose Equivalent per Unit Fluence [10] - The fluence-to-dose equivalent conversion factor is quite flat below ~ 40 keV; it increases by a factor of ~ 20 between 40 keV and 500 keV, and then increases relatively very slowly with further increase in energy. Hence the average dose equivalent per unit fluence for a spectrum is, to first order, only a function of the relative neutron populations above and below ~ 200 keV.

B. 9-Inch Sphere Remmeter - Its response peaks at a few MeV; the response is down by ~ 50% at 250 keV. Although its response does not fall off with decreasing energy quite as dramatically as does the fluence-to-dose equivalent conversion, it, too, can be considered as largely responsive to neutrons above ~ 200 keV. The similarity of its response as a function of neutron energy to that of the quantity dose equivalent per unit fluence is the justification for its use as a remmeter.

C. 3-Inch Sphere - Primarily sensitive to low energy neutrons, but its response is not peaked. It is basically flat from the cadmium cut-off (0.4 eV) to ~ 500 eV, and is down by a factor of 2 by ~ 100 keV.

D. 9-Inch/3-Inch Ratio - Since the 9-inch sphere is most sensitive to neutrons above 200 keV and the 3-inch sphere is most sensitive to neutrons below 100-200 keV, the 9-inch/3-inch ratio is then a strong function of the relative neutron energies above and below ~ 200 keV.

E. Albedo Dosimeter - Fairly flat response below a few keV, and then slowly drops off with increasing energy. Its response, per unit fluence, is down by a factor of two by ~ 200 keV. (We explicitly used the response function for the Hankins albedo dosimeter [9]. It has been shown, however [11], that the response function of most of the commonly used albedo dosimeters have the same shape, although the absolute sensitivity may vary.)

The response of these instruments in any spectrum is then largely a function of the relative number of neutrons above and below the 100 keV region. This may make it easier to understand why, for example, an albedo dosimeter will have approximately the same response to a neutron field produced by a ^{252}Cf source moderated by 15 cm or 20 cm of D_2O, as it has for the Alabama Power spectrum, even though the differential spectra are different (compare Figs. 2 and 4).

DEVELOPMENT OF A MODERATED Cf-252 SPECTRUM

The "ground rules" for the choice of a moderating assembly include the requirements that it be homogeneous and spherically symmetric so that the neutron field will be independent of orientation. It should be "reasonably" small and light lest problems in physical handling become an obstacle to its use as a neutron dosimeter calibration source. Finally, it should be made of materials whose cross sections are well known so that the spectrum can be accurately predicted.

The requirement that it be reasonably small and light means low-Z materials. Concrete is ruled out because of the difficulties in assuring uniformity from batch to batch. Beryllium is ruled out because of problems arising from its large (n,2n) cross section. Hence, the remaining choices are spherical moderators of graphite, or hydrogen or deuterium compounds.

The driving source should be ^{252}Cf, rather than Pu-Be, since the californium spectrum is well known, and the sources are physically small and reproducible, with negligible energy degradation in the encapsulation.

The data in Table I show that, for the various calculated moderators the thicker D_2O moderators yield results closest to those obtained for the Alabama Power and Light spectrum. It is clear that carbon is not a sufficiently efficient moderator. (It is well known, of course, that carbon can make an excellent moderator if it is big enough. The data in the Compendium of Ing and Makra [7] suggest that ~ 50 cm of carbon would give results comparable to 15 cm of D_2O. We feel that 50 cm (radius) is unreasonably large for use as an isotropic calibration source.) The Compendium also indicates that, as would be expected, beryllium is somewhat better and aluminum somewhat worse than graphite, but that D_2O is the best of these three.

Light water (H_2O) or polyethelene moderators were also considered, and found to be unsatisfactory for producing the desired spectrum. The reason probably lies in the fact that the deuterium cross section is relatively flat below ~ 1 MeV, whereas the hydrogen cross section continues to increase with decreasing neutron energy down to ~ 10 keV [12]. Hence, hydrogen will preferentially scatter neutrons <u>out</u> of the intermediate energy region. Comparison of Figs. 1 and 2 shows that this is exactly the opposite of what we are trying to achieve.

Figure 4 is the calculated spectrum for a 15 cm radius D_2O moderated fission source. Comparing the numbers in Table I, and comparing Figs. 2 and 4, shows that a 15 (or 20) cm D_2O moderator does not exactly duplicate the properties of the measured spectrum at the Alabama Power and Light reactor. Table I, however, shows that the D_2O moderated spectrum is similar to the Arkansas Power and Light calculated mid-cavity spectrum. As we have indicated earlier, the calculated Arkansas spectrum probably represents an upper absolute limit in terms of the spectral hardness to which personnel are likely to be exposed at reactors. Hence, while it might be desirable to have a still softer spectrum, the D_2O moderator does represent a much more realistic source for calibration purposes and for processor performance testing than would the much harder bare californium spectrum.

Referring again to Table I, it can be seen that increasing the radius of the D_2O moderator from 15 to 20 cm does not improve things appreciably. The 20 cm sphere would, however, weigh more than twice as much as the 15 cm sphere. In Fig. 5 we plotted the average dose equivalent for the spectra produced by various D_2O moderators, as a function of moderator weight. We believe that 15 cm is probably optimum, and it certainly doesn't seem justified to go beyond 20 cm radius of D_2O.

Hence, we concluded that ~ 15 cm D_2O moderator best simulates a nuclear reactor spectrum and represents a good compromise between the requirements for a realistic spectrum on one hand, and modest size and weight on the other. An additional virtue of the D_2O-moderated spectrum is that it provides a substantial neutron flux over the whole energy range from ~ 10 eV to ~ 5 MeV. Hence, this spectrum would prove generally useful for calibration and processor performance testing of a wide variety of dosimeters and remmeters.

DESIGN AND CONSTRUCTION OF MODERATED SOURCE

The NBS prototype moderated Cf source will be a 30-cm inside-diameter stainless steel shell (0.8 mm thick walls) containing the D_2O. This will be covered with a (removable) 0.5 mm cadmium shell, which may be used to absorb thermal neutrons. (See Fig. 7)

Much thought was given to the question of mounting the source in the sphere. The main consideration was safety in the use of the moderated source, and secondarily, minimizing extraneous material in the vicinity of the californium capsule. Thus, it was decided that the source should not be mounted permanently in the sphere, but rather placed in a capsule which could be readily removed from, or inserted into, the sphere. This allows the sphere to be positioned and manipulated in complete safety, with the source inserted only for actual irradiations. It also means that when not in use, only the source capsule need be shielded, rather than the whole sphere.

We also considered possible arrangements which might allow the californium source itself to be completely removed from the capsule so that the same source could be used for both "bare" and moderated irradiations. It became clear, however, that any such arrangement would either require extensive hand manipulation on the part of the user, leading to a high probability of overexposure, or involve the use of remote manipulations. While there is no objection to remote manipulation *per se*, it was felt that any manipulations should be kept very simple, to minimize the chance of anything going wrong, leaving the source in a position where it must be "rescued" by hand.

Hence, in the interests of safety and simplicity, it was decided to place the source in its own capsule (see Figs. 7 and 8) where hand manipulation is required only when the source is first loaded. After that, the capsule can, for example, be placed in the sphere by simply pulling on a string.

This encapsulation requires that two californium sources be available if it is desired to make both bare and moderated irradiations, and this does represent an additional initial expense. Table I shows, however, that the dose equivalent per unit fluence from the moderated source is approximately four times lower than that from the unmoderated source. Hence, for a given dose equivalent rate at a given distance from the sources, one would choose a californium source ~ 4 times as intense for the moderated source as for an unmoderated source. After ~ 2 half lives, however, the more intense source would then be of appropriate strength for unmoderated irradiations. Thus, although it is necessary to have two sources initially, it whould only be necessary to replace the more intense source, ~ every 5 years.

The calculations presented earlier in this report did not include the effects of the stainless steel shell, or stainless steel source capsule. The effect of the cadmium on the "epi-cadmium" neutrons is also not included. The calculations will shortly be expanded to take account of the stainless steel and cadmium shells. The effect of the stainless steel tubing for the Cf source will be calculated approximately. Both the shells and the tubing are expected to have negligible effect on the spectrum, however, since over most of the energy range of interest only a few percent of the neutrons will interact with either the steel or the cadmium, and the principle interaction will be elastic scattering with only a few percent energy loss.

Figure 7 is a cross sectional view of the sphere; figure 8 shows the source capsule; figure 9 is the source stem which screws into the source capsule. The source capsule will be filled with heavy water, so that the only void will be the ~ 0.4 mm radial clearance for the capsule.

CONCLUSIONS AND RECOMMENDATIONS

It must be emphasized that in the absence of an "ideal" dosimeter (as defined in the Introduction), one must be careful to choose a dosimeter which has an adequate response to the neutron spectrum of interest and to use a calibration source whose neutron spectrum is as close as is reasonably possible to the actual spectrum. In other words, the neutron dosimeter response, and the calibration source spectrum, should both be matched to the actual neutron spectrum of interest.

This report has been concerned with the problem of developing a neutron test and calibration source for use with dosimeters and remmeters employed in nuclear power reactor environments. The albedo dosimeter has been emphasized because it is the only available dosimeter with an adequate low energy response. We have shown that a ^{252}Cf source, moderated by 15 cm of heavy water, produces a neutron spectrum which is much closer to those measured in maintenance areas of power reactors than the bare Cf (or Pu-Be) sources used heretofore. Since the spectrum from this moderated source is still harder, however, than the model spectrum, use of this source for calibration will result in a "conservative" calibration factor for an albedo dosimeter. For example, a dosimeter which is calibrated with the moderated source and then used at the Alabama Power and Light reactor will over-estimate the dose equivalent by a factor of ~ 3. By contrast, the same dosimeter, used at the same reactor, but calibrated with a bare ^{252}Cf source, would over-estimate the dose-equivalent by a factor of 35!

We therefore strongly recommend that the moderated ^{252}Cf source be used for testing and calibrating dosimeters to be used near power reactors, and that the dosimeter itself should respond to low and intermediate energy neutrons. The albedo dosimeter is the most appropriate of the currently available devices, whereas dosimeters based on NTA film alone should not be considered acceptable.

On the other hand, for neutron dosimetry in environments with "hard" spectra, such as at high energy accelerators or around glove boxes, NTA film or track etch dosimeters would be appropriate, and a bare source could be used for testing and calibration.

The prototype moderated source is now under construction, and NBS will be using it for prototype testing and calibration. We also envisage one, or several, testing laboratories being designated by the NRC, each with its own moderated source (based on the NBS model), as well as a bare californium source. These testing laboratories could carry out such tests and calibrations as the NRC may require, using either the bare or the moderated source, as appropriate for the particular dosimeter and its application.

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[4] H. M. Butler, W. F. Ohnesonge, and J. A. Auxier, loc. cit. 611.

[5] G. L. Simmons, private communication.

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[10] *Fluence-to-dose equivalent conversion factors taken from NCRP Report* No. 38, p. 16 (1971).

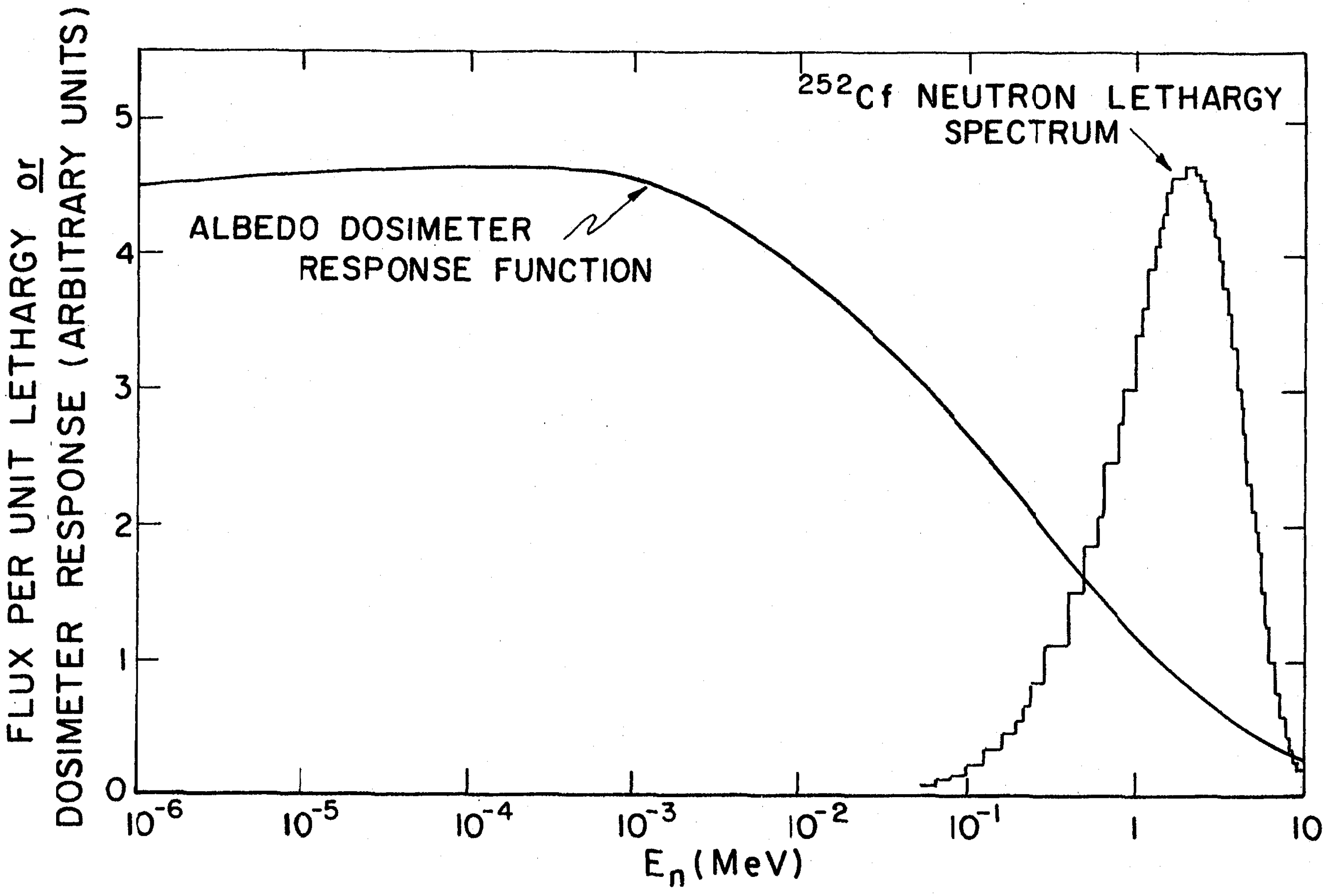
[11] E. Piesch and B. Burgkhardt, Proc. Seventh DOE Workshop on Personnel Neutron Dosimetery, London, England (1978) p. 25.

[12] D. J. Hughes and R. B. Schwartz, "Neutron Cross Sections" BNL 325 (1958).

TABLE I. CALCULATED RESPONSES PER UNIT FLUENCE

Spectrum	Average Dose Equivalent $\frac{\text{mrem}}{(\text{n/cm}^2)}$	Albedo Dosimeter Response $\frac{\text{Reading}}{(\text{n/cm}^2)}$	Dosimeter Calibration Factor $\frac{\text{Average DE}}{\text{Dos. Resp.}}$	9-Inch Sphere $\frac{\text{Counts}}{(\text{n/cm}^2)}$	3-Inch Sphere $\frac{\text{Counts}}{(\text{n/cm}^2)}$	9"/3" Ratio
^{252}Cf unmoderated	32.2-6[a]	4.4-6	7.27	27.8	15.5	1.79
Moderated in 20 cm C	18.8-6	8.6-6	2.17	18.9	24.7	0.77
Moderated in 10 cm H_2O	21.2-6	8.6-6	2.47	19.8	19.8	1.00
Moderated in 10 cm D_2O	13.3-6	10.9-6	1.22	15.3	28.8	0.53
Moderated in 15 cm D_2O	8.5-6	13.4-6	0.64	11.3	27.7	0.41
Moderated in 20 cm D_2O	6.3-6	14.7-6	0.43	9.1	24.9	0.36
Alabama Power and Light (Personnel Environment)	3.0-6	14.7-6	0.21	7.6	28.7	0.27
Arkansas Power and Light (Reactor Leakage)	8.7-6	12.2-6	0.71	12.1	28.2	0.43

[a] 32.2-6 $\equiv 32.2 \times 10^{-6}$, etc.



^{252}Cf NEUTRON LETHARGY SPECTRUM
ALBEDO DOSIMETER RESPONSE FUNCTION
FLUX PER UNIT LETHARGY or DOSIMETER RESPONSE (ARBITRARY UNITS)
0
1
2
3
4
5
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
E_n (MeV)

Figure 1

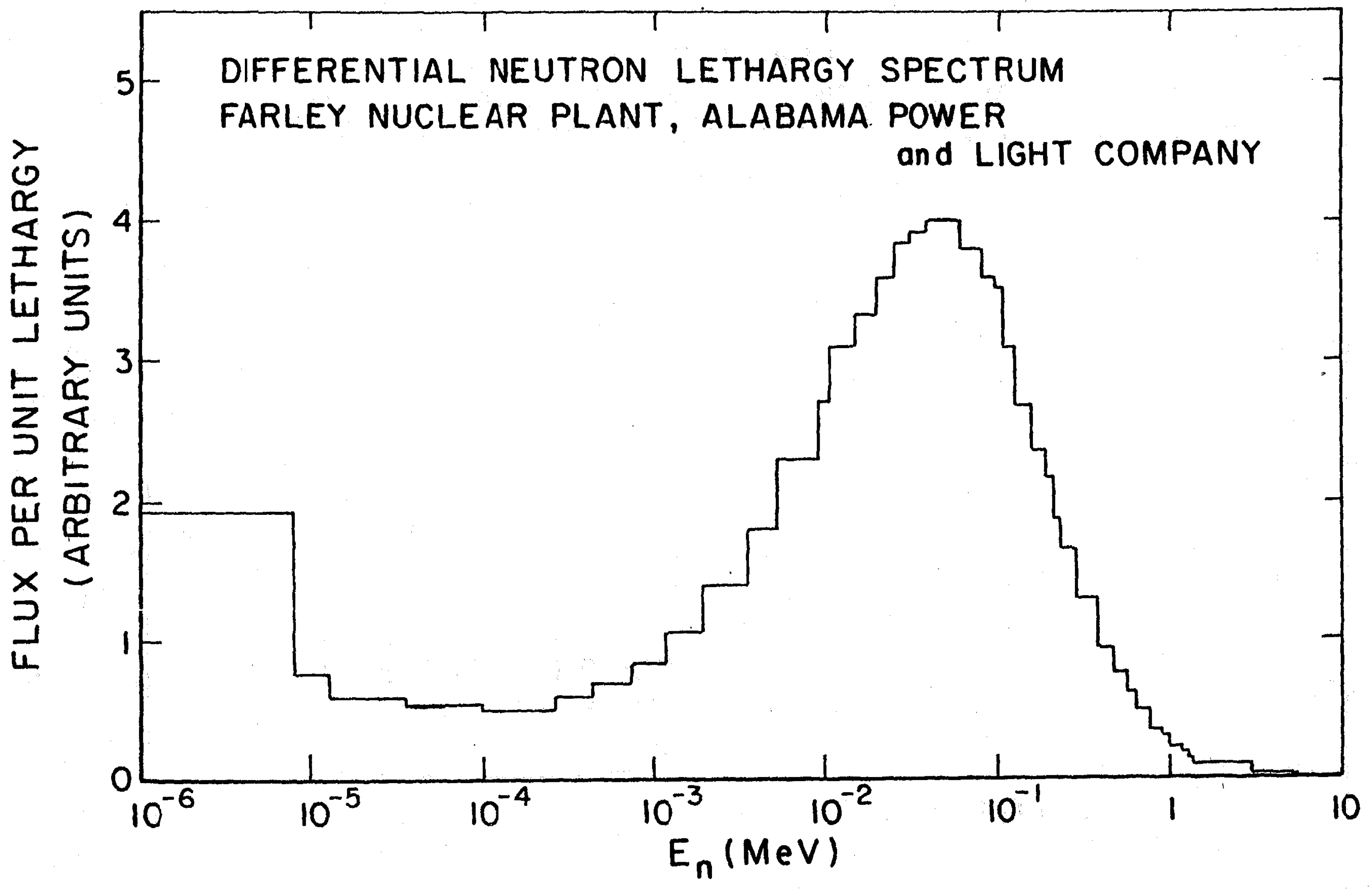

DIFFERENTIAL NEUTRON LETHARGY SPECTRUM
FARLEY NUCLEAR PLANT, ALABAMA POWER
and LIGHT COMPANY
FLUX PER UNIT LETHARGY
(ARBITRARY UNITS)
0
1
2
3
4
5
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
E_n (MeV)

Figure 2

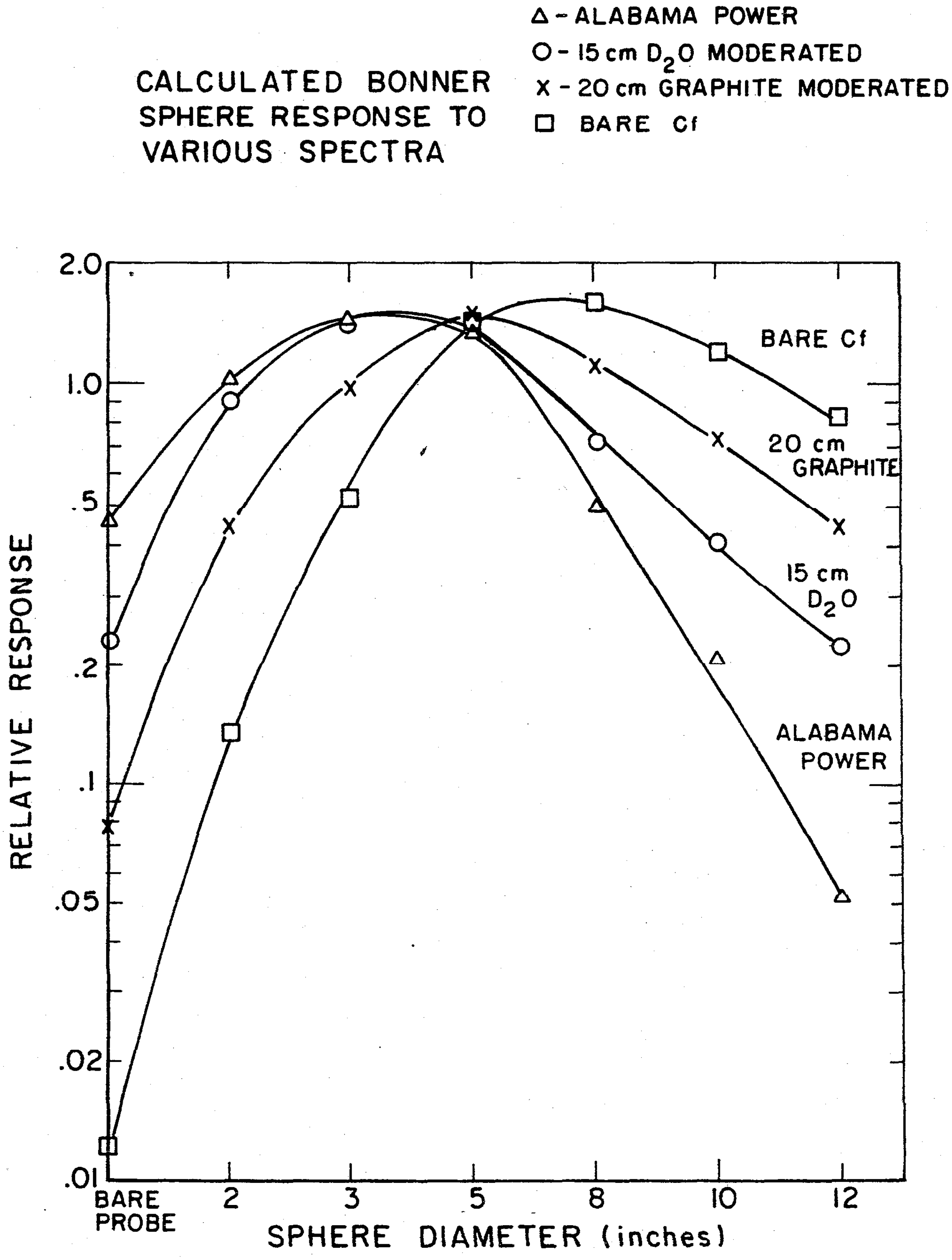

CALCULATED BONNER SPHERE RESPONSE TO VARIOUS SPECTRA
Δ - ALABAMA POWER
O - 15 cm D_2O MODERATED
X - 20 cm GRAPHITE MODERATED
□ BARE Cf
RELATIVE RESPONSE
2.0
1.0
.5
.2
.1
.05
.02
.01
BARE PROBE
2
3
5
8
10
12
SPHERE DIAMETER (inches)
BARE Cf
20 cm GRAPHITE
15 cm D_2O
ALABAMA POWER

Figure 3

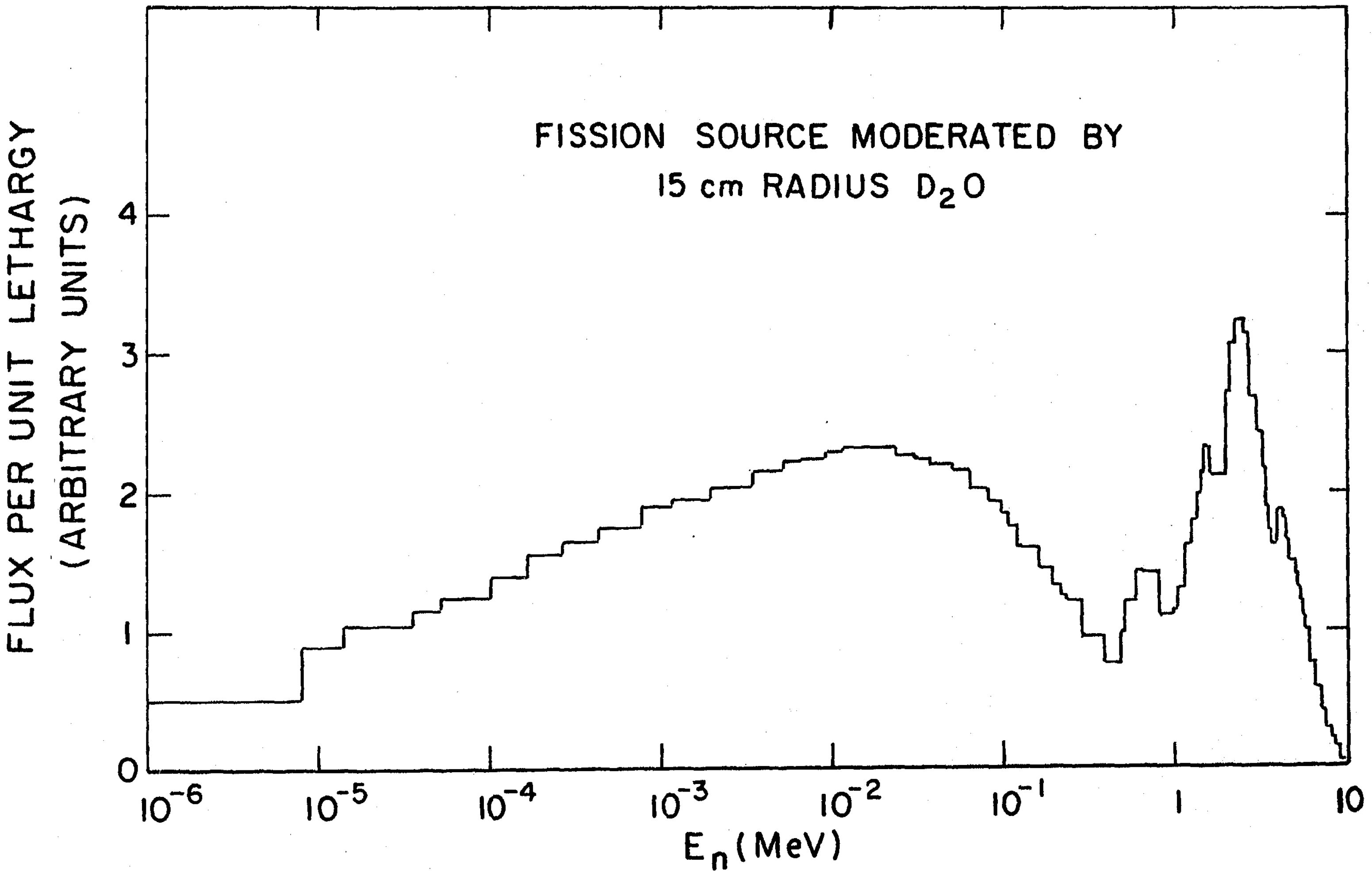

FISSION SOURCE MODERATED BY
15 cm RADIUS D_2O
FLUX PER UNIT LETHARGY
(ARBITRARY UNITS)
0
1
2
3
4
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
E_n (MeV)

Figure 4

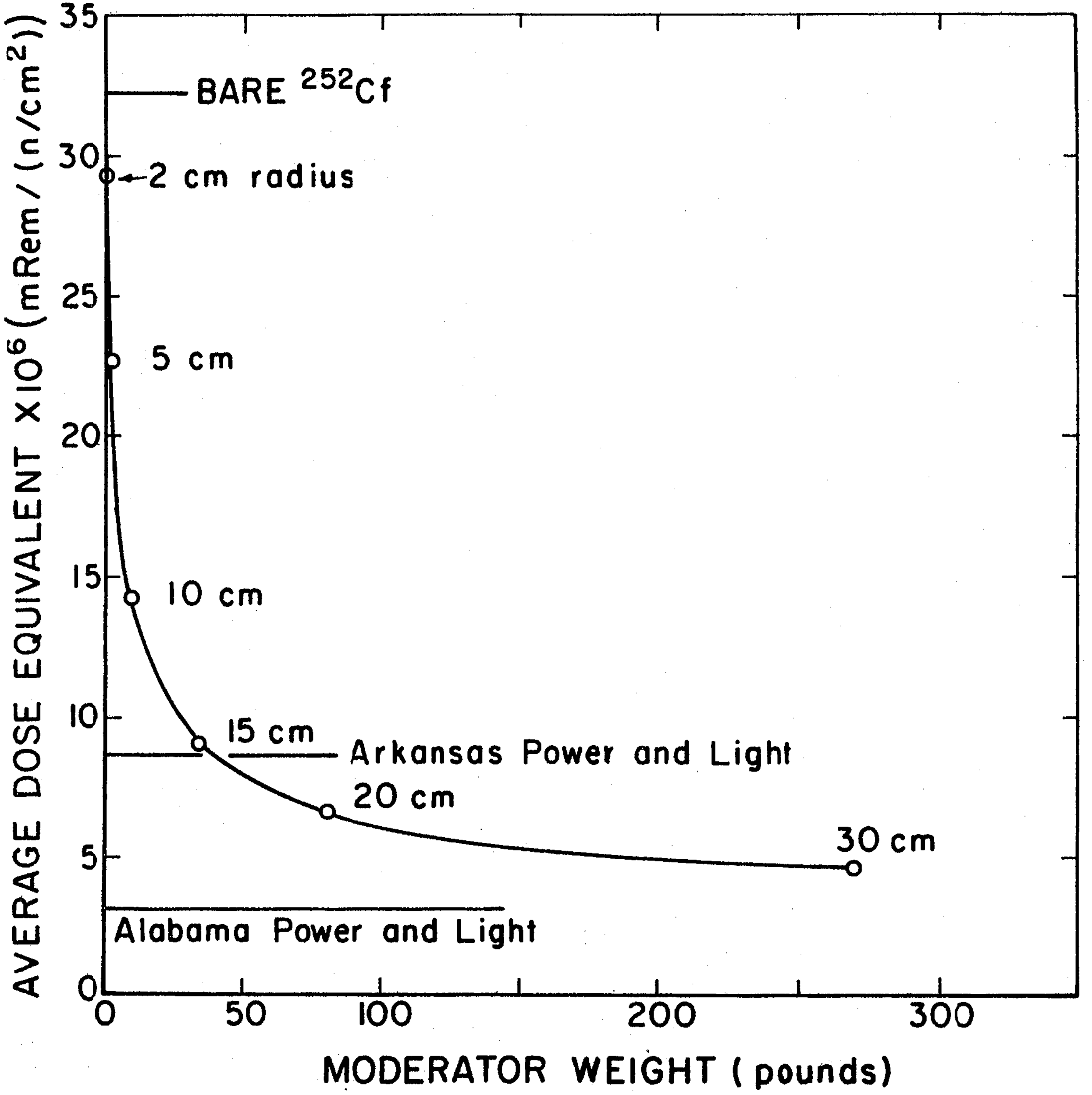

BARE ^{252}Cf
←2 cm radius
5 cm
10 cm
15 cm
Arkansas Power and Light
20 cm
30 cm
Alabama Power and Light
AVERAGE DOSE EQUIVALENT X10^6 (mRem / (n/cm^2))
0
5
10
15
20
25
30
35
0
50
100
200
300
MODERATOR WEIGHT (pounds)

Figure 5

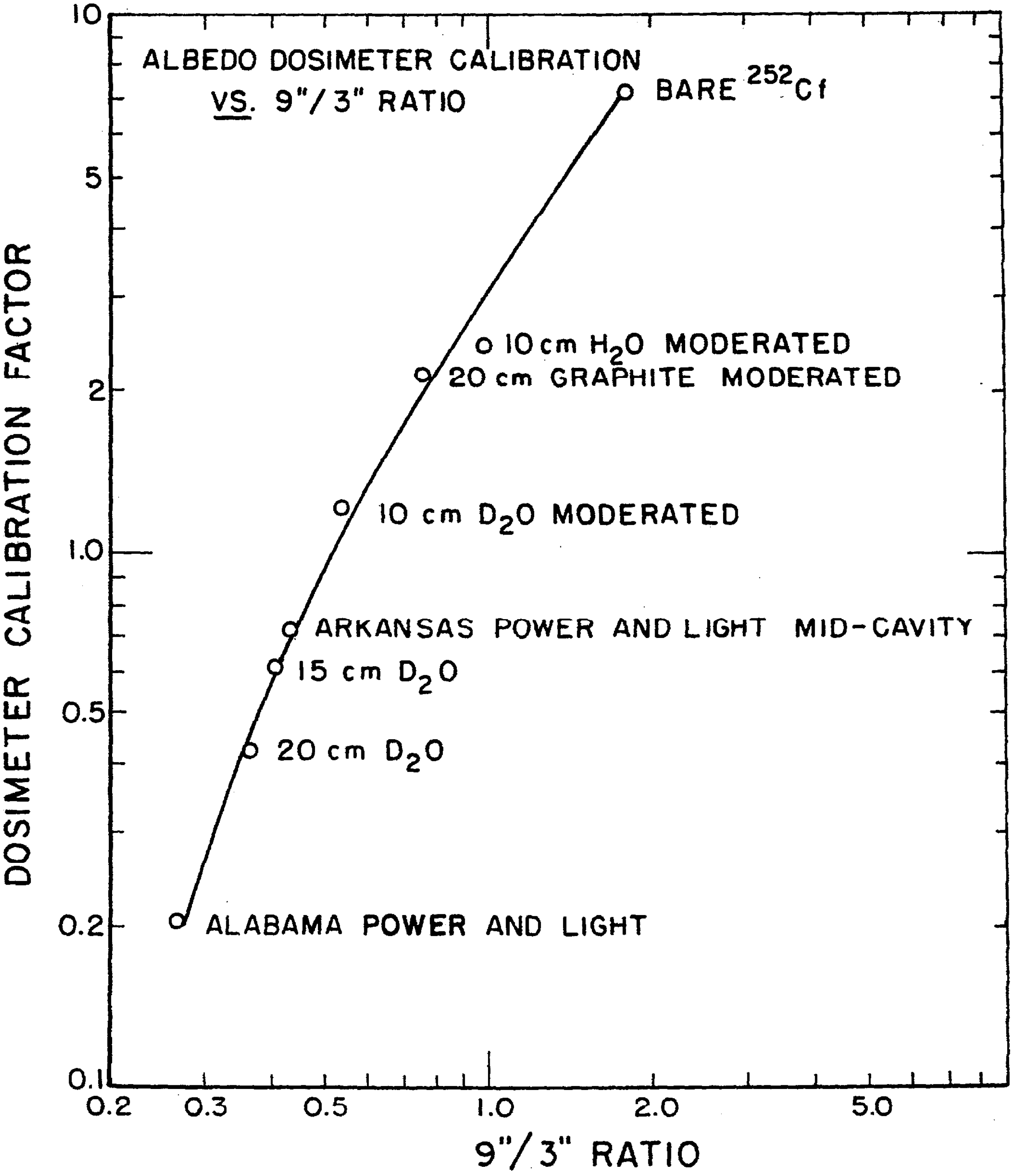
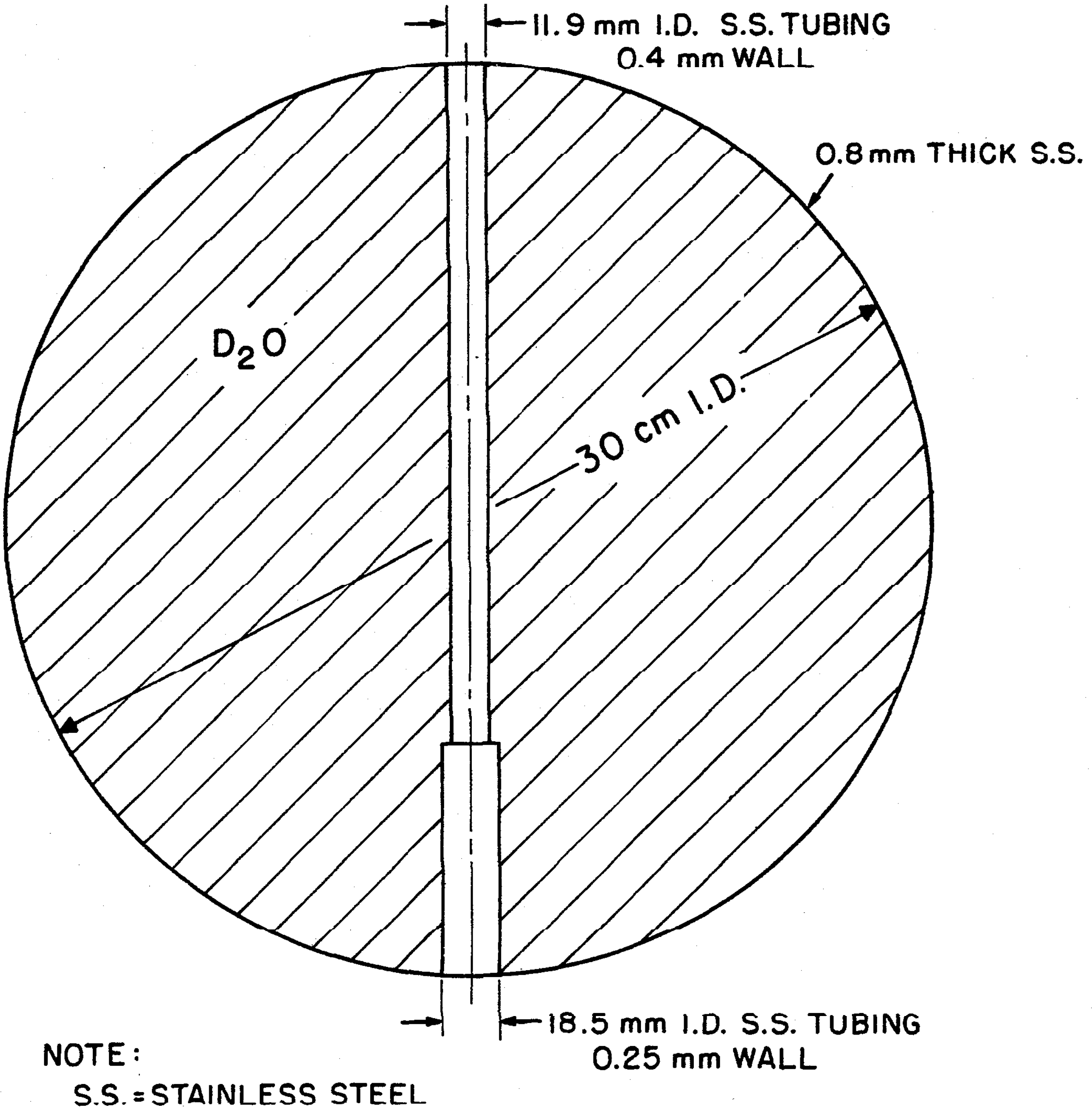
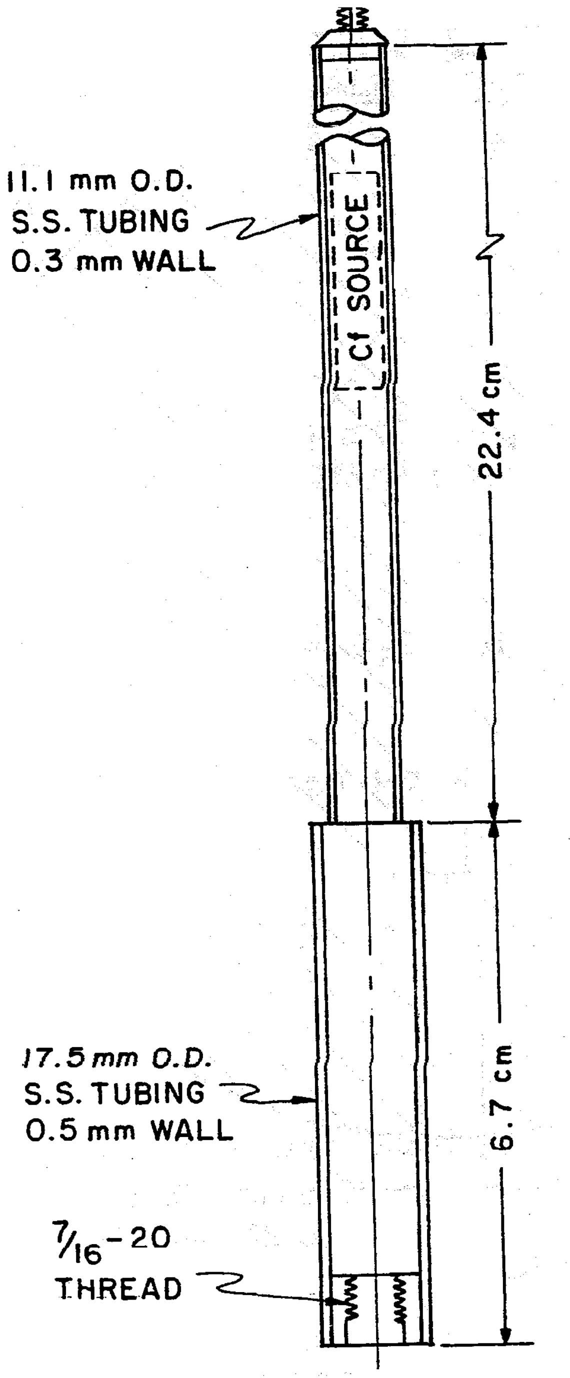

ALBEDO DOSIMETER CALIBRATION
VS. 9"/3" RATIO
BARE ^{252}Cf
10 cm H_2O MODERATED
20 cm GRAPHITE MODERATED
10 cm D_2O MODERATED
ARKANSAS POWER AND LIGHT MID-CAVITY
15 cm D_2O
20 cm D_2O
ALABAMA POWER AND LIGHT
DOSIMETER CALIBRATION FACTOR
10
5
2
1.0
0.5
0.2
0.1
0.2
0.3
0.5
1.0
2.0
5.0
9"/3" RATIO

Figure 6



HEAVY WATER SPHERE

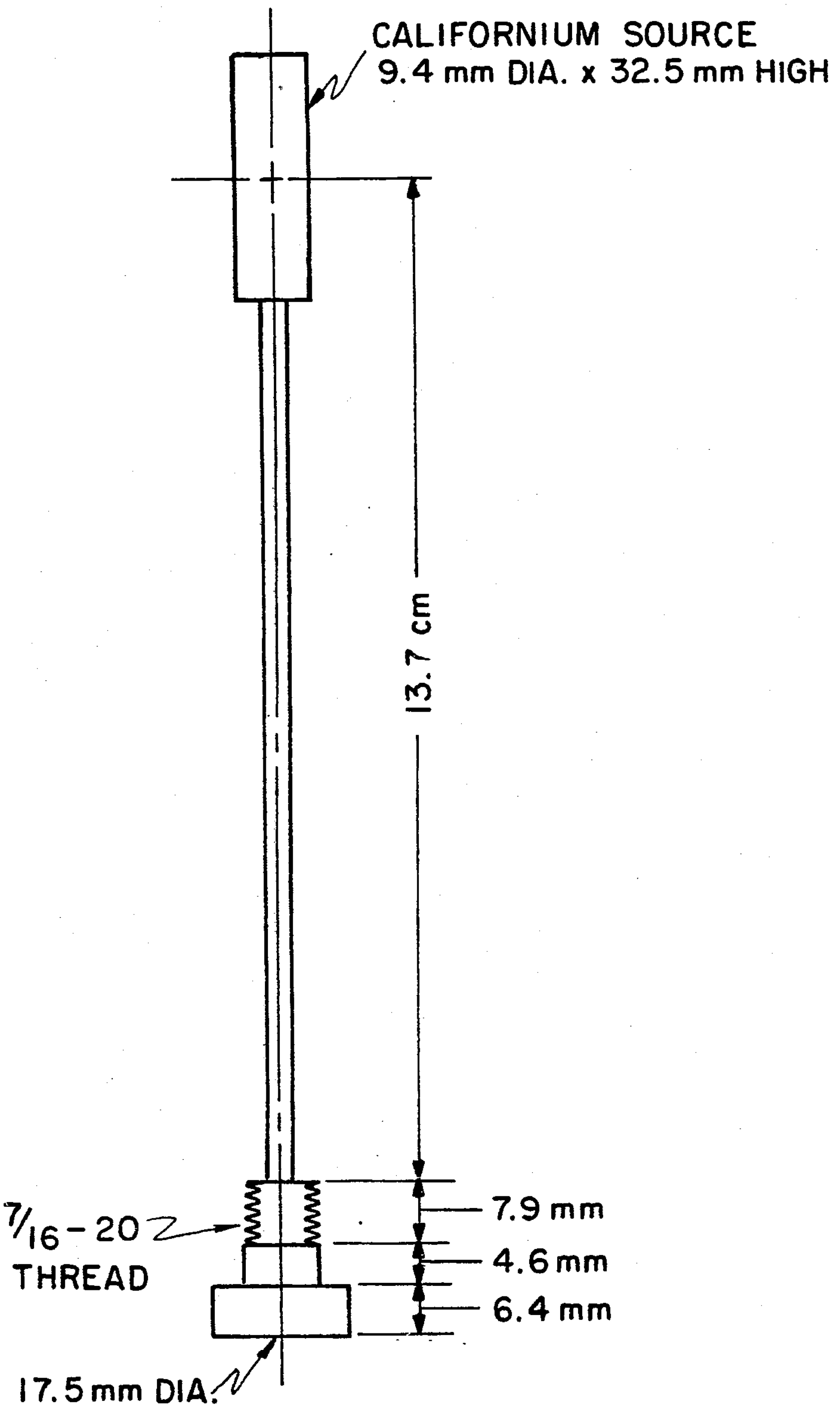
Figure 7



(TO BE FILLED WITH HEAVY WATER)

SOURCE CAPSULE

Figure 8



SOURCE STEM
STAINLESS STEEL

Figure 9