Design calculations for the ANS cold source

R. A. Lillie and R. G. Alsmiller
Engineering Physics and Mathematics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee
USA

ABSTRACT: The calculational procedure, based on discrete ordinates transport methods, that is being used to carry out design calculations for the Advanced Neutron Source cold source is described. Calculated results on the gain in cold neutron flux produced by a liquid-deuterium cold source are compared with experimental data and with calculated data previously obtained by P. Ageron, *et al.*, at the Institute Max von Laue-Paul Langevin in Grenoble, France. Calculated results are also presented that indicate how the flux of cold neutrons vary with cold-source parameters.

Introduction

The Advanced Neutron Source (ANS) is a new experimental facility being planned by the Oak Ridge National Laboratory to meet the national need for an intense steady-state source of neutrons[1,2,3]. The facility will be built around a new research reactor and will have the largest neutron flux available anywhere in the world. The ANS will be equipped with advanced neutron scattering and nuclear physics research facilities, with isotope production facilities, and with facilities for the study of materials in strong radiation fields.

A major purpose of the ANS is to provide a high flux of cold ($\lesssim 10^{-2}$ eV) neutrons for experiments. High fluxes of such cold neutrons can be obtained from a liquid deuterium (~20 K) region in the reflector tank outside of a high-flux reactor. Such a system has been in operation for some time at the Institute Max von Laue-Paul Langevin (ILL) in Grenoble, France[4]. In this paper some of the calculations that have been done to aid in the design of a liquid-deuterium cold source for the ANS will be described and the results discussed.

ANS geometry and method of calculation

ANS reactor and reflector. The ANS is in the preconceptual design stage. The base concept for the ANS reactor is a very compact core (30 to 40 L active volume) with a very high-density fuel of U_3Si_2 in an aluminum matrix. The coolant and reflector/moderator surrounding the core are heavy water. Preliminary calculations show an unperturbed peak thermal flux of $\sim 10^{20}$ n/m^2 s at a power level of ~300 MW and give a core life of approximately 14 d[5].

A preconceptual reactor design for the ANS in a single-core configuration has been developed by the Oak Ridge National Laboratory (ORNL) and in a split-core configuration by the Idaho National Engineering Laboratory (INEL)[6,7]. Both designs were analyzed independently by both laboratories and very satisfactory agreement was obtained. As part of these studies, the neutron flux per unit energy throughout the reflector region was calculated at ORNL using the discrete ordinates transport code DORT[8]. In the remainder of this paper, these calculated flux values for the INEL split-core design will be used as the basis for the calculations.

More details of the work that has been done to date and the design and performance calculations will be found in Refs. 2, 3, 6, 7, 9-11.

Reactor geometry, cold-source geometry, and coupling surfaces. To simplify the calculations as much as possible, they will be carried out in a two-dimensional r-z geometry. In Fig. 1 two cylindrical geometries—the reactor geometry and the cold-source geometry—are depicted. The reactor geometry, in the absence of the cold source, has cylindrical symmetry about the reactor z-axis; it is the geometry in which the neutron flux throughout the reflector was calculated previously and is available for use in the calculations described here. The cold-source geometry has cylindrical symmetry about the cold-source z-axis that is perpendicular to the reactor-geometry z-axis.

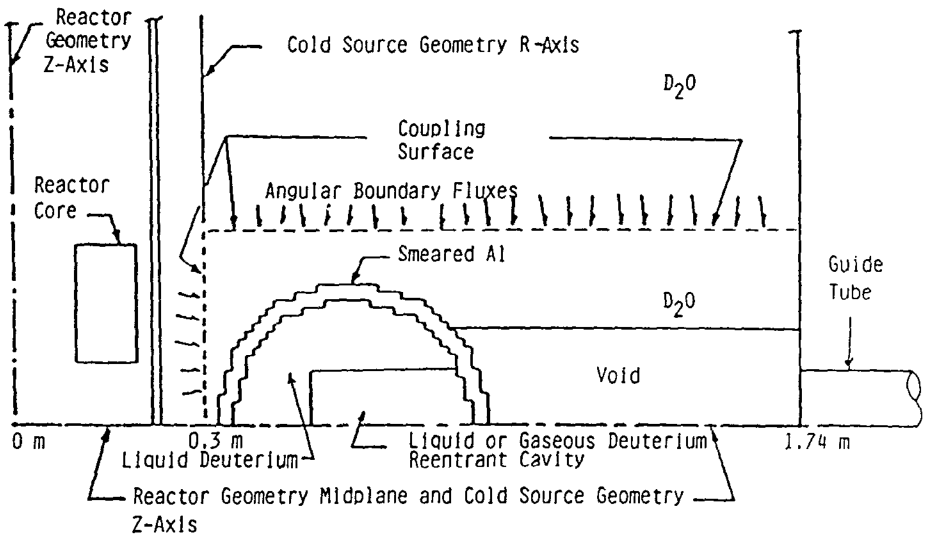

Fig. 1 Reactor and cold-source geometries with coupling surface.

An auxiliary code has been developed to transform particle fluxes from discrete ordinates calculations between between two r-z geometries, such as those shown in Fig. 1. The transformation code constructs the boundary angular fluxes needed to perform a cold-source calculation from the volume-distributed angular fluxes determined in a reactor geometry. The method consists of performing a spatial and angular transformation to equate the angular fluxes at each radial, azimuthal and axial boundary mesh point to the angular flux at the closest mesh point and angular direction in the reactor geometry. Azimuthal symmetry is taken into account by employing a one-dimensional Gaussian quadrature to integrate over the azimuthal mesh points. Because of the relatively small number of angular directions employed in most discrete ordinates calculations, the boundary angular fluxes obtained using this nearest neighbor approach do not, in general, conserve boundary leakage. Therefore, boundary angular currents both before and after the transformation are calculated and employed to scale the output boundary fluxes. The boundary fluxes at the coupling surface (dashed lines in Fig. 1) are approximate because they were determined from the angular flux per unit energy that exist in the absence of the cold source and are used in the presence of the cold source. Also in the cold-source geometry, azimuthal symmetry is assumed; this symmetry does not exist in the reactor geometry. To test the validity of these approximations, the thermal neutron flux, as a function of distance along the cold-source z-axis as obtained in the reactor geometry and in the cold source geometry when the cold source, void tube, etc., are replaced by D_2O have been compared and found to be in good agreement.

Transport calculations. The cold-source transport calculations were carried out for the geometry inside the dashed lines in Fig. 1. This geometry begins at a distance of 0.30 m from the reactor-geometry z-axis and extends to 1.44 m along the cold-source z-axis and 0.45 m along the cold-source r-axis. The value of z = 1.74 m in Fig. 1 is approximately the position where the neutron guide tubes will begin. Only liquid deuterium is considered as the cold-source material. The liquid-deuterium region is shown as approximately circular in Fig. 1, but may be any shape. In the remainder of this paper, a cylindrical guide tube with its axis along the axis of the cold source will be considered. The re-entrant cavity is for the purpose of studying the effect of such a cavity on the cold-source performance because this effect has been found to be significant[4,12,13].

The quantity of primary interest is the flux of cold neutrons that emerge from the guide tubes at the experiment stations. The reflection properties of the guide tubes are such that cold neutrons at grazing angles with respect to the walls of the guide tubes will be reflected and, thus, transported over quite long distances to the experimental stations[14]. The quantity of interest in the calculations is, therefore, the angular leakage of cold neutrons that exit the void region behind the cold source and enter the guide tube (see Fig. 1), or more precisely, the cold neutrons that enter the guide tube at small angles (~ few degrees) with respect to the cold source z-axis.

The transport calculations were carried out using the two-dimensional discrete ordinates code DORT[8] and the last flight code FALSTF[15]. All of the DORT calculations were carried out using an S_8 symmetric angular quadrature and a P_3 angular expansion of the scattering cross section. To obtain the angular neutron leakage at small angles, the code FALSTF was used because the symmetric S_8 angular quadrature set employed in the DORT calculations does not contain discrete directions pointed down the axis of the void region. FALSTF calculated the flux at point detectors located outside the DORT calculational geometry using the final scattering source distribution produced by DORT. With a thin layer of black absorber located in the cold-source geometry to ensure that only neutrons which pass through the entrance of the guide tube are counted, the neutron flux at a point detector located a large distance R from the entrance to the guide cavity is simply the angular neutron leakage into the guide cavity entrance divided by R^2. Thus, multiplying the neutron flux at a number of point detectors located at different distances from the z-axis by R^2 yields the directional angular neutron leakage into the guide cavity.

Cross section data. A coupled neutron-photon multigroup cross-section library designated ANSL-V (for Advanced Neutron Source Library based on ENDF/B-BV) has been developed for use in ANS studies[16,17]. A fine-group library containing 99 neutron- and 44 photon-groups and a broad-group library containing 39 neutron- and 44 photon-groups have been generated. For low energy studies of particular interest here, the fine-group library contains 29 neutron groups between 1.00×10^{-5} and 3.00 eV and the broad-group library contains 25 groups in this energy range.

Of particular interest here is the cross-section model used to describe the very low temperature scattering of neutrons by ortho- and para-deuterium. The model used is not yet documented, but is not appreciably different from the free gas model developed by J. A. Young and J. U. Koppel[18,19]. The calculated cross sections deviate significantly from available experimental data[20] at energies below approximately 2×10^{-3} eV. It has been established by the work of W. Bernnat, *et al.*[21], and M. Utsuro[22] that this discrepancy can be substantially reduced by the use of a liquid rather than a gas model, but results from this more accurate model have not yet been incorporated into the ANSL-V library.

For many of the studies considered here, it was convenient to use fewer than 39 neutron groups. When this was the case, the 39-group library was collapsed with XSDRN[23] and a one-dimensional model of ANS.

Results and discussion

The gain factor may be defined to be the ratio of the angular leakage of neutrons, with a given wavelength, from the cold source into the guide tube (see Fig. 1) to this angular leakage when the cold-source material is replaced by D_2O. In Fig. 2 the calculated and measured gain factor for a liquid-deuterium-filled spherical cold source with a radius of 190 mm is shown[12]. In Fig. 2 the calculated results of P. Ageron, *et al.*[4,12,13], as well as those reported here are shown.

In the calculations reported here, the geometry used is that shown in Fig. 1. A guide tube radius of 55 mm, which corresponds to that used in the experiment, was used. This geometry differs in detail from the experimental geometry, but the differences are not thought to have an appreciable effect on the results. Also, the neutron source used in the calculations is that used throughout the paper since the actual source distribution in the experiment is not available. Since the gain factor that is compared involves a ratio, the details of the source may not have a significant effect on the results.

The histogram in the figure is for an angle of 0°. The calculated results for an angle of 3° is very similar to that for 0° and is, therefore, not shown. The angular range of 0° to 3° is chosen to cover the wavelength range of interest (~0.1 to 1 nm) for the possible guide-tube materials[14]. The calculated results obtained here are slightly higher than those obtained by P. Ageron, *et al.*, but are somewhat lower than the measured values.

Calculations carried out using the 39 neutron groups, as in Fig. 2, require very long computing times, which are much too long for design calculations that must be repeated many times. For routine use, the 39-group cross sections have been reduced to a 6-group cross-section set. In Table 1 calculated results of the neutron angular leakage at 0° into the guide tube obtained with the 39-group and the 6-group cross sections are presented. The geometry used in obtaining the results in Table 1 is that shown in Fig. 1 with a spherical liquid-deuterium cold source with a radius of 190 mm. The void-tube radius was 146 mm, the guide-tube radius was 85 mm, and there was no cavity. In the results shown in Table 1 and throughout the remainder of this paper, the liquid deuterium used will be taken to have a density of 0.8 of the theoretical density to account for the fact that gaseous deuterium will be present; also, the liquid deuterium is assumed to be uniformly distributed over the cold-source volume.

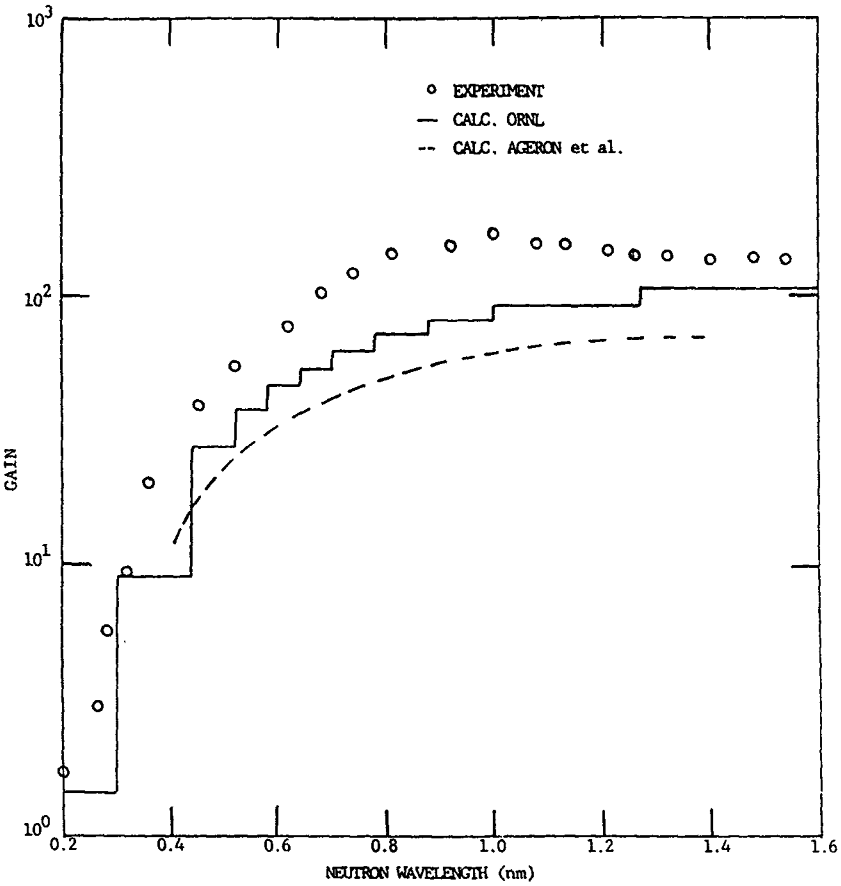

Fig. 2 Gain vs. neutron wavelength.

Neutron Group	Upper[1] Energy (eV)	Lower[2] Wavelength (nm)	Angle from Cold Source Centerline = 0 Degrees (neut./s/ster) 39 Group Calc.	Sum 39 Group Calc.	6 Group Calc.	Sum 39 Group / 6 Group
1 (1)	2.00+7[3]	6.40-6	1.84+13	3.33+14	2.27+14	1.47
2	6.43+6	1.13-5	9.79+13			
3	3.00+6	1.65-5	7.05+13			
4	1.85+6	2.10-5	2.37+13			
5	1.40+6	2.42-5	1.96+13			
6	9.00+5	3.02-5	2.58+13			
7	4.00+5	4.52-5	7.74+13			
8 (2)	1.00+5	9.05-5	2.09+14	1.39+15	1.80+15	0.77
9	1.70+4	2.19-4	3.00+14			
10	3.00+3	5.22-4	3.91+14			
11	5.50+2	1.22-3	4.93+14			
12 (3)	1.00+2	2.86-3	3.98+14	4.03+15	1.64+16	0.25
13	3.00+1	5.22-3	4.03+14			
14	1.00+1	9.05-3	5.11+14			
15	3.00+0	1.65-2	5.87+14			
16	1.77+0	2.15-2	4.75+14			
17	1.30+0	2.51-2	4.38+14			
18	1.00+0	2.86-2	5.70+14			
19	7.65-1	3.27-2	6.44+14			
10 (4)	5.88-1	3.73-2	4.99+14	4.20+16	3.79+16	1.11
21	4.79-1	4.13-2	4.31+14			
22	3.97-1	4.54-2	4.96+14			
23	3.30-1	4.98-2	4.58+14			
24	2.70-1	5.51-2	6.64+14			
25	2.15-1	6.17-2	9.58+14			
26	1.62-1	7.11-2	1.72+15			
27	1.04-1	8.87-2	6.69+15			
28	5.00-2	1.28-1	8.12+15			
29	3.00-2	1.65-1	2.20+16			
30 (5)	1.00-2	2.86-1	2.16+16	4.07+16	3.44+16	1.18
31	4.45-3	4.29-1	8.34+15			
32	3.25-3	5.02-1	4.84+15			
33	2.60-3	5.61-1	3.38+15			
34	2.15-3	6.17-1	2.52+15			
35 (6)	1.80-3	6.74-1	2.40+15	8.05+15	6.40+15	1.25
36	1.45-3	7.51-1	1.87+15			
37	1.15-3	8.44-1	1.61+15			
38	8.50-4	9.81-1	1.24+15			
39	5.50-4	1.22+0	9.47+14			

[1]Lower energy of Group 39 is 1.00-5 eV.

[2]Upper wavelength of Group 39 is 9.05 nm.

[3]2.00+7 read as 2.00×10^7.

Table 1 Neutron angular leakage into neutron guides (spherical liquid deuterium cold source with radius = 190 mm, void tube radius = 146 mm, guide tube radius = 85 mm, no cavity).

In Table 1 the energy group and corresponding wavelength-group boundaries are shown. For purposes of comparison, the appropriate 39-group results have been summed; these summed results are also given in Table 1. There are significant differences between the 39-group and the 6-group results, but the differences are not so major as to make the 6-group results completely untrustworthy. Calculated results similar to those in Table 1, for an angle of 3° have also been obtained and are not appreciably different from the results shown in Table 1.

The results discussed above were all for a guide tube of radius 85 mm. In Table 2, the calculated angular leakage at 0° and 3° is presented for a range of guide-tube radii. The case considered is as before, i.e., a spherical liquid-deuterium cold source with a radius of 190 mm and a void-tube radius of 146 mm. As indicated in the table, guide-tube radii of 37, 61, 85, and 146 mm are considered.

Neutron Energy Group	Upper[1] Energy (eV)	Lower Wavelength (nm)	Neutrons/s/Ster Neutron Guide Tube Radius (mm) 37	61	85	146
			Angle from Cold Source Centerline = 0°			
1	2.00+7[3]	6.40-6	3.88+13	1.13+14	2.27+14	6.94+14
2	1.00+5	9.05-5	3.07+14	8.94+14	1.78+15	5.66+15
3	1.00+2	2.86-3	2.85+15	8.19+15	1.64+16	5.21+16
4	5.88-1	3.73-2	6.81+15	1.90+16	3.79+16	1.20+17
5	1.00-2	2.86-1	6.12+15	1.75+16	3.44+16	1.01+17
6	1.80-3	6.74-1	1.13+15	3.25+15	6.40+15	1.83+16
			Angle from Cold Source Centerline = 3°			
1	2.00+7	6.40-6	4.13+13	1.13+14	2.31+14	5.31+14
2	1.00+5	9.05-5	3.15+14	9.04+14	1.88+15	4.33+15
3	1.00+2	2.86-3	4.15+15	9.64+15	1.87+16	4.13+16
4	5.88-1	3.73-2	6.64+15	1.97+16	4.11+16	9.23+16
5	1.00-2	2.86-1	5.72+15	1.73+16	3.54+16	7.73+16
6	1.80-3	6.74-1	1.07+15	3.21+15	6.52+15	1.41+16

[1]Lower energy of Group 6 is 1.00-5 eV.
[2]Upper wavelength of Group 6 is 9.05 nm.
[3]2.00+7 read as 2.00×10^7.

Table 2 Neutron angular leakage into guide tubes of different radii (spherical liquid deuterium cold source with radius = 190 mm, void tube radius = 146 mm, no cavity).

The values in the table are given for completeness, but can be compared more readily by taking ratios. First, it is clear that the leakage into the guide tube is nearly proportional to the area of the guide tube. To remove this effect, the values in Table 2 must be divided by the guide-tube cross sectional area. Second, the angular leakage in a given energy group for a guide tube of 85 mm will be taken as a normalizing factor, and the results for the other guide tubes will be divided by this normalizing value. The results, when this is done, are shown in Fig. 3 as a function of guide-tube radius for the lowest three energy groups considered. The plotted points indicate the calculated values. The curves are only for guidance and, particularly in the 3° case, are somewhat arbitrary.

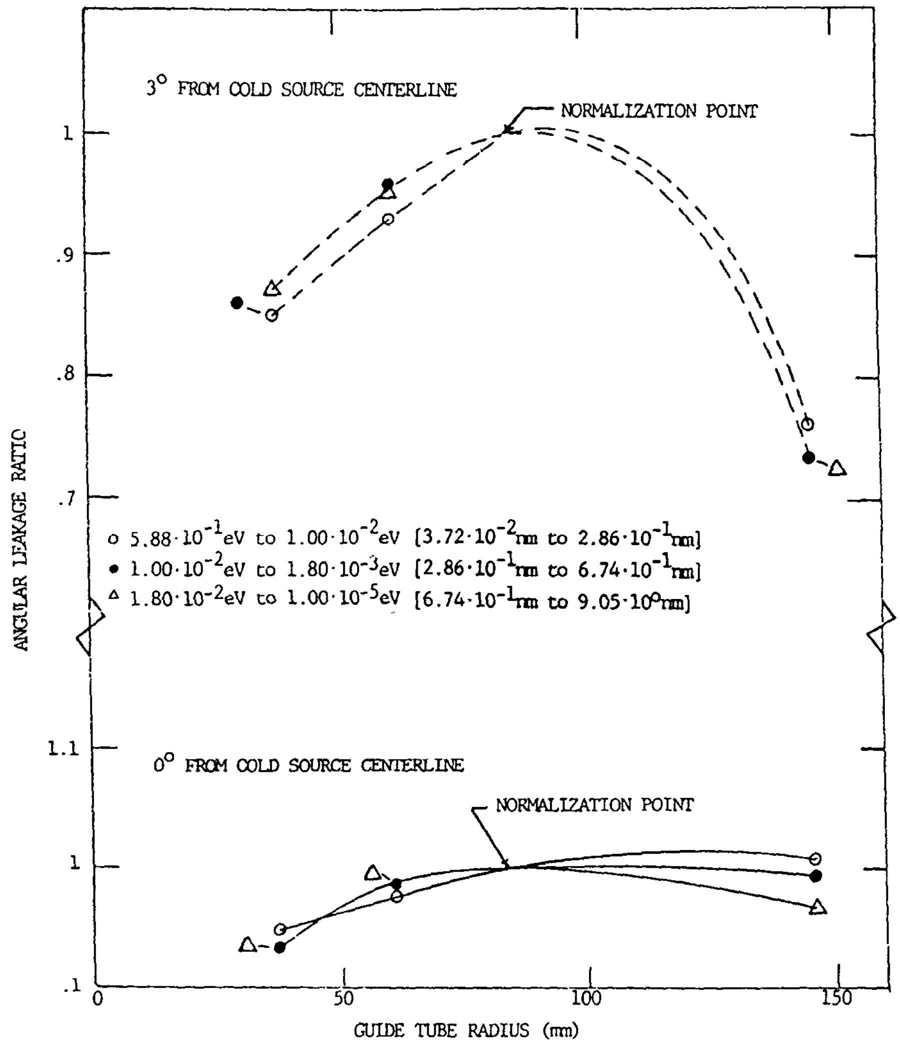

Fig. 3 Ratio of angular leakage in a given energy range into a guide tube of specified radius to angular leakage into guide tube of radius 85 mm vs, guide tube radius. (Spherical cold source with radius = 190 mm, void tube radius = 146 mm, no cavity.)

In the 0° case, the change of the leakage with guide-tube radius is not large. For each of the energy groups considered, there appears to be an optimum guide-tube radius, but not a very precise one. In the 3° case, the variation of the leakage with guide-tube radius is larger than the 1° case. It is also clear that there is an optimum guide-tube radius for each of the groups considered; but with only the points that are shown in Fig. 3, it is not possible to estimate the position of the optimum or the magnitude of leakage at the optimum.

At the ILL it has been found that a re-entrant cavity, such as that shown in Fig. 1, can significantly increase the flux of cold neutrons in the guide[4,12,13]. A series of calculations with a spherical cold source of radius 190 mm and various re-entrant cavities has been carried out to study this phenomena. The neutron source and void-tube radius are the same as that used previously. The cavity radius and the guide-tube radius are taken to be the same and equal to 85 mm. Cavity lengths of 134 mm, 219 mm, and 256 mm are considered.

In Fig. 4 the calculated neutron flux in the energy range 1.8×10^{-3} eV to 1.0×10^{-2} eV is shown along the cold-source centerline as a function of distance from the front, i.e., the reactor side, of the cold source. In the figure, results are shown for the three different re-entrant tube lengths and for the case when there is no cavity.

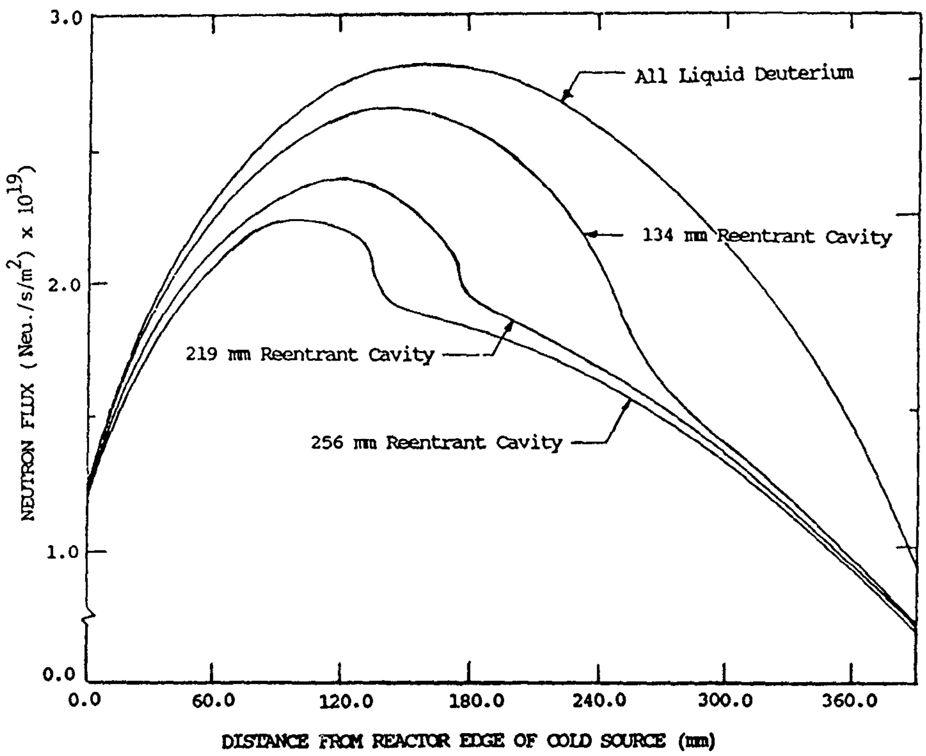

Fig. 4 Low energy flux (1.8×10^{-3} eV < E < 1.0×10^{-2} eV) profiles through center of spherical cold source.

In all cases, the flux reaches a maximum and then decreases. As the length of the cavity increases (see Fig. 1), the maximum value of the flux decreases and the position of the maximum value is closer to the front of the cold source. In the three curves for the re-entrant cavities, the position to the right of the flux peak, where the curves have a change in slope, is the position of the interface between the liquid deuterium and the cavity. Note that the flux at the entrance to the cavities is larger than the flux at the entrance to the void tube in the case of no cavity.

In Table 3 the angular leakage into the guide tube is shown for the three cavities considered and the case of no cavity. In the table, results are given for all energy groups and for angles 0°, 1°, 2° and 3°. The values in the table are again given for completeness, but can be more readily understood by considering ratios.

Neutron Energy Group	Upper[1] Energy (eV)	Lower[2] Wavelength (nm)	(neutrons/s/ster) Angle from Beam Tube Centerline (degrees) 0	1	2	3
			All liquid deuterium			
1	2.00+7[3]	6.40-6	2.27+14	2.23+14	2.26+14	2.31+14
2	1.00+5	9.05-5	1.78+15	1.79+15	1.81+15	1.88+15
3	1.00+2	2.86-3	1.64+16	1.64+16	1.67+16	1.87+16
4	5.88-1	3.73-2	3.79+16	3.82+16	3.91+16	4.11+16
5	1.00-2	2.86-1	3.44+16	3.44+16	3.49+16	3.54+16
6	1.80-3	6.74-1	6.40+15	6.40+15	6.48+15	6.52+15
			134 mm reentrant cavity			
1	2.00+7	6.40-6	5.61+14	5.02+14	4.71+14	4.31+14
2	1.00+5	9.05-5	3.98+15	3.59+15	3.37+15	3.19+15
3	1.00+2	2.86-3	2.95+16	2.71+16	2.59+16	2.66+16
4	5.88-1	3.73-2	4.32+16	4.15+16	4.16+16	4.41+16
5	1.00-2	2.86-1	4.35+16	4.06+16	3.89+16	3.94+16
6	1.80-3	6.74-1	9.18+15	8.41+15	7.87+15	7.78+15
			219 mm reentrant cavity			
1	2.00+7	6.40-6	9.99+14	8.65+14	7.87+14	6.73+14
2	1.00+5	9.05-5	6.74+15	5.89+15	5.35+15	4.65+15
3	1.00+2	2.86-3	4.43+16	3.93+16	3.65+16	3.42+16
4	5.88-1	3.73-2	4.97+16	4.67+16	4.63+16	4.60+16
5	1.00-2	2.86-1	4.26+16	3.96+16	3.80+16	3.60+16
6	1.80-3	6.74-1	9.14+15	8.31+15	7.78+15	7.06+15
			256 mm reentrant cavity			
1	2.00+7	6.40-6	1.24+15	1.07+15	9.57+14	8.12+14
2	1.00+5	9.05-5	8.26+15	7.14+15	6.38+15	5.51+15
3	1.00+2	2.86-3	5.18+16	4.56+16	4.16+16	3.85+16
4	5.88-1	3.73-2	5.30+16	4.93+16	4.83+16	4.80+16
5	1.00-2	2.86-1	3.92+16	3.68+16	3.54+16	3.42+16
6	1.80-3	6.74-1	8.33+15	7.64+15	7.15+15	6.61+15

[1]Lower energy of group 6 is 1.00-5 eV.
[2]Upper wavelength of group 6 is 9.05 nm.
[3]2.00+7 read as 2.00×10^7.

Table 3 Neutron angular leakage into 85.3 mm radius neutron guide tube (void tube radius = 146.3 mm, cavity radius = 85.3 mm).

In Fig. 5 the ratio of the angular leakage in a given energy range with a cavity present to the corresponding angular leakage with no cavity is shown as a function of cavity length. Results are shown for angles of 0° and 3°. At 0° the maximum value of the ratio obtained is slightly less than 1.5 and is for the highest energy group shown that is group 4. For group 5, the maximum value obtained is considerably smaller; for group 6, the maximum value obtained is slightly smaller. For groups 4 and 5, the maximum value of the ratio occurs between lengths 134 mm and 219 mm; but for group 6, the maximum value occurs at the largest cavity length considered. At 3° the ratios have similar behavior, but the values are, in general, smaller than at 0°; for groups 4 and 5, the maximum value of the ratio occurs at smaller values of the cavity length.

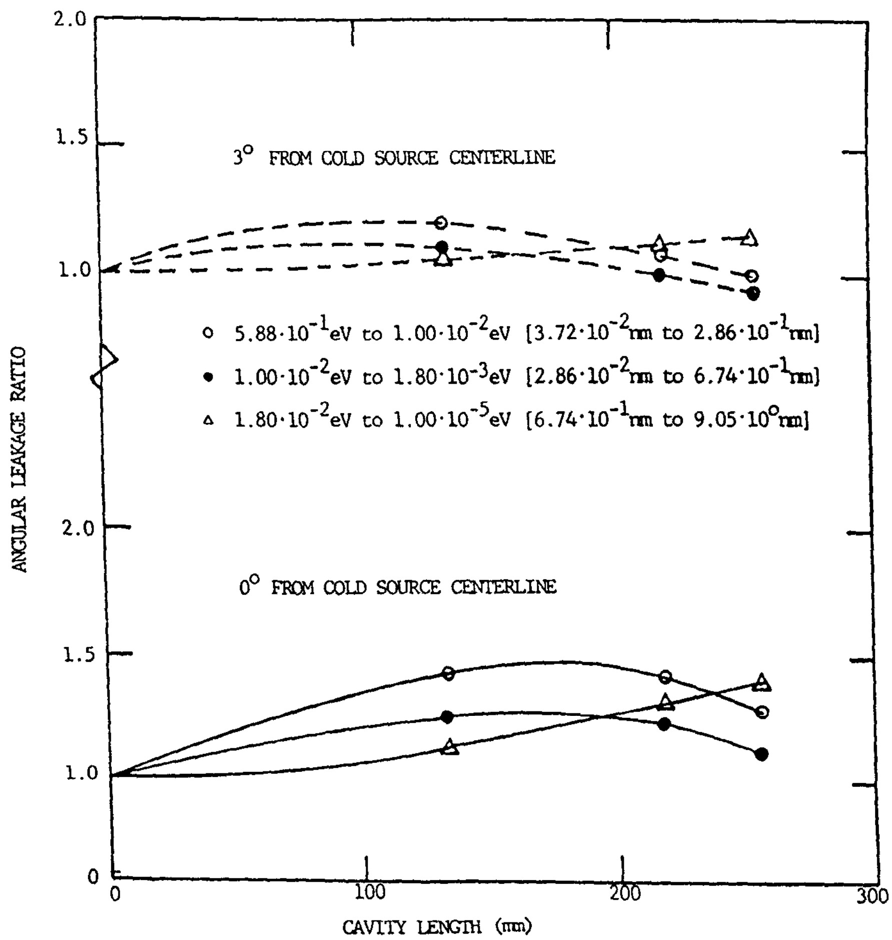

Fig. 5 Ratio of angular leakage in a given energy range from cold source with re-entrant cavity to angular leakage from cold source with no cavity vs. cavity length. (Spherical cold source with radius = 190 mm, void tube radius = 146 mm, cavity radius = 85 mm, guide tube radius = 85 mm.)

P. Ageron has presented both measurements and calculations of the effects of re-entrant cavities on the flux of cold neutrons produced by liquid-deuterium cold sources. Detailed calculations from ORNL for comparison with these results are not yet available, but from the preliminary results that have been obtained, it is clear that the ORNL results will not agree well with those of Ageron, *et al.* In general, the results in Refs. 4, 11, and 12 indicate improvements in the wavelength range 0.1 to 1 nm due to cavities to be factors of 1.5 and above, and our calculation gives values such as those in Fig. 5 of 1.5 or significantly less.

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References

1. A. Zucker, "The Advanced Neutron Source - An Ultrahigh Flux Research Reactor," presented at the International Symposium on the Utilization of Multi-Purpose Research Reactors and Related International Cooperation, Grenoble, France.
2. D. L. Selby, *et al.*, 1987, "ORNL Contributions to the Advanced Neutron Source (ANS) Project for October 1986 - March 1987", Oak Ridge National Laboratory ORNL/TM-10579.
3. D. L. Selby, *et al.*, 1988,"ORNL Contributions to the Advanced Neutron Source (ANS) Project for October 1986 - March 1987", Oak Ridge National Laboratory ORNL/TM-10860.
4. P. Ageron, "Special Neutron Sources", 1985, Proceedings of Conference on Neutron Scattering in the Nineties", organized by the International Atomic Energy Agency and held at Jülich Nuclear Research Center, January 14-18, IAEA-CN-46/16.
5. C. D. West, 1988, "Overview of the ANS Project", to be presented at the American Nuclear Society/European Nuclear Society 1988 International Conference, Washington, D. C., October 30 - November 3, and included in the transactions.
6. D. L. Selby and J. L. Lake, 1988, "ANS Core Comparison Workshop Summary", Oak Ridge National Laboratory ORNL/ANS/INT-4.
7. J. M. Ryskamp, *et al.*, 1988, "Comparison of Single and Split Core Concepts for the Advanced Neutron Source", to be presented at the Topical Meeting on Reactor Physics, Jackson Hole, Wyoming, September 18-22, and published in the proceedings.
8. DORT is the CRAY computer version of the DOT-IV code. See W. A. Rhoades and R. L. Childs, "An Updated Version of the DOT 4 One- and Two-Dimensional Neutron/Photon".
9. J. M. Ryskamp, D. K. Parsons, and J. A. Lake, 1986,"Ultrahigh Flux Double Donut Research Reactor Design", Proc. Topl. Mtg. Reactor Physics and Safety, Saratoga Springs, New York, September 17-19, 1986, NUREG/CP-0080, 2, 780, U.S. Nuclear Regulatory Commission.

10. F. C. Difilippo, *et al.*, 1986, "An Intense Steady-State Neutron Source - The CNR Reactor", Proc. Topl. Mtg. Reactor Physics and Safety, Saratoga Springs, New York, September 17-19, 1986, NUREG/CP-0080 2, 792, U.S. Nuclear Regulatory Commission.
11. J. M. Ryskamp, 1969, "Preconceptual Core Design of the Advanced Neutron Source", to be presented at the American Nuclear Society/European Nuclear Society 1988 International Conference, Washington, D.C. October 30 - November 3, and included in the transactions.
12. P. Ageron, *et al.*, 1969, "Experimental and Theoretical Study of Cold Neutron Sources of Liquid Hydrogen and Liquid Deuterium", Cryogenics 42.
13. P. Ageron, 1978, "Neutron Flux Calculations for the Deuterium Cold Sources in Siloette and in HFR", Institute Max Von Laue-Paul Langevin, DTE-781650-PA/ngd.
14. C. D. West, *et al.*, 1986, "Center for Neutron Research Project Status Report", Oak Ridge National Laboratory ORNL/TM-10065.
15. "FALSTF, Informal Notes", 1979, CCC-351, Radiation Shielding Information Center, Oak Ridge National Laboratory.
16. J. W. Arwood, *et al.*, 1987, "Preparation and Benchmarking of ANSL-V Cross Section Library for Advanced Neutron Source Reactor Studies", Transactions of the 1987 Winter Meeting of the American Nuclear Society, November 15-19, Los Angeles, California.
17. D. L. Selby, *et al.*, 1987, "ORNL Contributions to the Advanced Neutron Source Project for October 1986-March 1987, Oak Ridge National Laboratory ORNL/TM-10579.
18. J. A. Young and J. U. Koppel, 1964, "Slow Neutron Scattering by Molecular Hydrogen and Deuterium", Phys. Rev. A135, 603.
19. M. W. Waddell, 1987, private communication.
20. N. D. Seiffert, 1970, "Measurement of Scattering Cross Sections of Liquid and Solid Hydrogen Deuterium and Deuterium-Hydride", EUR4455d.
21. W. Bernnat, 1988, "Evaluation of Neutron Cross Sections for Liquid Hydrogen and Deuterium for the Design of Cold Neutron Source", Proc. of International Conference on Nuclear Data for Science and Technology, Mito, Japan, May 30-June 3.
22. M. Utsuro, 1977, "Slow Neutron Scattering and Intermolecular Excitation in Liquid Hydrogen", Z. Physik B27, 111.
23. N. M. Greene and C. N. Craven, Jr., 1969, "XSDRN, A Discrete Ordinates Spectral Averaging Code", Oak Ridge National Laboratory ORNL/TM-2500.