PROGRESS REPORT

STUDY OF NEUTRON FOCUSING AT THE TEXAS COLD NEUTRON SOURCE

DE-FG02-92ER75711

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CONTENTS

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I. INTRODUCTION

Funds were received for the first year of a three year DOE Nuclear Engineering Research Grant, "Study of Neutron Focusing at the Texas Cold Neutron Source" (DE-FG02-92ER75711). The purpose of this three year study is to develop a neutron focusing system to be used with the Texas Cold Neutron Source (TCNS) to produce an intense beam of neutrons. A prompt gamma activation analysis (PGAA) facility will also be designed, setup, and tested under this DOE grant.

During the first year of the DOE grant, a new procedure was developed and used to design a focusing converging guide consisting of truncated rectangular cone sections. Detailed calculations were performed using a 3-D Monte Carlo code which we wrote to trace neutrons through the existing curved guide of the TCNS into the proposed converging guide. Using realistic reflectivities for Ni-Ti supermirrors, we obtained gains of 4 to 5 for the neutron flux averaged over an area of 1 x 1 cm.

Two graduate students were supported by the first year of the DOE grant. Both have passed the Nuclear Engineering qualifying examination and have been admitted to candidacy for the doctoral degree at The University of Texas at Austin. Their programs of study and dissertation projects have been approved by the appropriate committees.

II. NEUTRON FOCUSING SYSTEMS

Because of recent advances in the fabrication of Ni coated silicon wafers and Ni-Ti multilayers for supermirrors, two methods of neutron focusing were considered for use with the TCNS. We had proposed an in-depth study on how to best utilize these new advances for the construction of a neutron focusing system based on one or the other method or possibly both methods in a tandem configuration.

One of the methods for neutron focusing utilizes many thin Ni coated silicon wafers (microguides) stacked together and bent such that each microguide points to the desired point in space [1]. Silicon wafers of a thickness of 10 μm are available commercially (Virginia Semiconductor Inc. 1501 Powhatan St. Fredericksburg, VA 22401). These wafers can be coated with 100 nm of nickel on both sides. Although they are brittle, they show some flexibility for bending.

Stacking many curved microguides on top of one other with their ends slightly overlapping like a shifted stack of playing cards could increase the neutron flux along a line in space. However, the required precise arrangement of the microguides would necessitate high precision machining and aligning of thousands of silicon wafers. After consultation with the NIST group, we abandoned the idea of building a microguide focusing system.

The second method for neutron focusing is based on converging the beam with supermirrors [2-12]. Converging guides using Ni-Ti supermirrors have been applied at ILL, Grenoble, France where a neutron fluence amplification of 2.5 was obtained [13]. However, there were reflectivity losses of 38% of the integral number of neutrons per second. With a new technique developed by Ovonic Synthetic Materials Company (1788 Northwood, Troy, MI 48084) multilayers of Ni-Ti of 33 x 10 cm area have been obtained with substantially better reflectivity [14].

In order to achieve an increase in neutron flux, the critical angle for neutron reflection from the surfaces of the TCNS converging guide must be greater than the critical angle for Ni-58 since our curved guide is coated with Ni-58. This dictates coating the converging guide surfaces with Ni-Ti supermirror layers having an effective critical angle of 0.3° for 1-Å neutrons [4]. Recent advances in supermirror technology have produced reflectivities greater than 95% for angles of neutron reflection up to this effective critical angle [14].

We have spent considerable time and effort over the last six months working with Ovonic Synthetic Materials Company on selecting the materials to be used for the converging guide system. They proposed to provide us a converging guide made to our design specifications out of glass with the Ni-Ti layers deposited on the glass. However, this turned out to be considerably more expensive than they first had indicated it would be when we submitted our initial proposal to DOE.

An alternative converging guide material was suggested which would be less expensive. The body of the converging guide would be made of aluminum with thin layers of Si glued on the aluminum. The multilayer supermirror would be deposited on the Si. However, this system is still more expensive than the amount we had budgeted for construction of the focusing system. See the informal quotes attached to the renewal proposal from Ovonics dated January 25, and 28, 1993.

III. DESIGN OF FOCUSING CONVERGING GUIDE

The goal of a neutron focusing apparatus for absorption experiments is to increase the flux at the expense of angular divergence. Several geometries and shapes have been suggested to obtain neutron focusing with minimal reflectivity losses, logarithmic spiral [15], a conical mirror which may be square or cylindrical in cross section, etc. During the grant period of FY 1992, we developed a procedure to design a converging guide consisting of truncated rectangular cone sections (Fig. 1). The converging guide would be located at the far end of the existing curved guide. This arrangement is shown schematically in Fig. 2.

The procedure which was developed to design the converging guide maximizes the neutron flux over an area 1 x 1 cm at the focal point of the converging guide by varying the two slant angles, α_1 and α_2, (Fig. 1) for each truncated rectangular cone section as the sections are added one at a time. This was done by using a 3-D Monte Carlo simulation that traced 4-Å neutrons through both the curved guide and the converging guide. The resulting set of slant angles is a good approximation to the set that would be obtained using a global optimization since only a small fraction of the neutrons suffer more than one reflection in the converging guide.

Several analytical calculations on the performance of neutron guides were found in the literature [16-19], but these calculations were carried out in two dimensions with a spatially uniform "isotropic in 2D" neutron source. These 2-D treatments could not be used for designing a converging guide because neutron reflections from all four walls (top, bottom, and 2 sides) are important. Also, the spatial distribution of neutrons entering the converging guide is not uniform and the angular distribution is not "isotropic in 2D." By "isotropic in 2D" we mean $dn/d\phi$ is constant where ϕ is the polar angle in 2 dimensions. An isotropic 3-D source would have $dn/d\Omega$ constant where Ω is the solid angle in 3 dimensions.

Thus, we wrote our own 3-D Monte Carlo code to trace neutrons through neutron guides. To have the correct spatial and angular distributions for neutrons which enter the converging guide, neutrons were first transported through the curved guide and then through the converging guide for all calculations. The neutron source at the reactor end of the curved guide was assumed to be uniform and isotropic in 3D.

In order to verify that the results of our 3-D Monte Carlo code are correct, we did benchmark calculations. Neutron transport through one channel of our curved guide was selected as the benchmark. Monoenergetic neutrons of 4-Å wavelength were used as the source. The dimensions of the one channel guide are: length = 6 m, radius of curvature = 300 m, width = 4.5 mm, and height = 50 mm. The spatial and angular distributions for neutrons exiting the curved guide channel were calculated using the following methods:

a) 3-D Monte Carlo with a spatially uniform isotropic-in-3D source,

b) 2-D analytical calculation with a spatially uniform "isotropic-in-2D" source,

c) 2-D analytical calculation with a spatially uniform "equivalent-3D" source.

The results of the benchmark calculations for the spatial distribution of neutrons exiting at the end of the guide integrated over the height of the guide are shown in Fig. 3. The 3-D Monte Carlo calculation was done with our 3-D Monte Carlo code with a uniform isotropic source, (a). Another code was written to perform the 2-D analytical calculation by integrating over possible trajectories for zig-zag and garland reflections. The first 2-D calculation, (b), had a 2-D source uniform in space and isotropic in 2-D angle (shown as a dashed line in the insert of Fig. 3). The 2-D calculation was repeated, (c), with a 2-D angular distribution obtained from a 3-D isotropic angular distribution (also shown in the insert of Fig. 3, solid line). The shape of the spatial distribution (Fig. 3.) obtained by the 3-D calculation agrees well with the shape of the distribution obtained by the 2-D calculation with "equivalent 3-D source." The total number of neutrons is slightly larger, however, because the top and bottom surfaces reflect fewer neutrons than sides that go to infinity. The shape of the distribution obtained by the 2-D calculation with the 2-D source is somewhat different, but the magnitude agrees with the 2-D calculation having the "equivalent 3-D source." By comparing the distributions shown in Fig. 3 and other results obtained in the benchmark calculations, we concluded that our Monte Carlo calculations give correct results.

Using our 3-D Monte Carlo code, two different converging guide systems were designed, one with four 20-cm long sections and the other with eight 20-cm long sections. As previously explained, our design procedure involved varying the two slant angles for each truncated rectangular cone section to give maximum flux over a 1 cm^2 area at the focal point as the sections are added one at a time. The slant angles and corresponding dimensions for the 80-cm and 160-cm long converging guides are given in Table I.

We define gain as the mean current density over a 1 x 1 cm area at the focal point of the converging guide divided by the mean entrance current density over the 15.5 x 50 mm area at the entrance to the converging guide. The gains for our two designs are 4.2 and 5.2 for the 80-cm and 160-cm long guides, respectively. The calculated spatial distributions for 4-Å neutrons entering the converging guide from the curved guide and exiting the converging guide at the focal point are shown in Fig. 4 for the 160-cm long converging guide.

IV. STUDENT INVOLVEMENT AND RELATED DEVELOPMENTS FOR TCNS AND NDP

Mr. Jong-Youl Kim, supported by this DOE grant, was admitted to candidacy for the doctoral degree at The University of Texas at Austin during this reporting period. The subject of his dissertation is the design and analysis of a focusing converging guide to be used with the TCNS. His research will also include using the converging-guide TCNS system for Neutron Depth Profiling measurements. Mr. Kim's Ph.D. committee includes Dr. Greg Downing of NIST, an internationally known scientist for NDP.

Plans for the Prompt Gamma Activation Analysis facility to be used with the focusing converging guide were finalized during this reporting period. Mr. Carlos Rios-Martinez, supported by this DOE grant, was also admitted to candidacy for the doctoral degree; the subject of his dissertation is the design, construction, and use of a PGAA facility using focused cold neutrons. Mr. Rios-Martinez's Ph.D. committee includes Dr. Richard Lindstrom of NIST, a well known scientist for PGAA. Our plans for a PGAA facility were reported in a talk given by Mr. Rios-Martinez (attached) at Tercer Congreso Anual, Instituto de Investigaciones Eléctricas Cuernavaca, Mor., November 22, 1992.

The construction of the Texas Cold Neutron Source (TCNS) was completed early in the DOE-grant reporting period utilizing funds provided by the State of Texas. The results of this work were reported in 2 transactions (attached) given at the 1992 ANS Annual Meeting at Boston. The thermal performance of the TCNS was then determined by a series of measurements, the initial thermal tests being reported in a transaction (attached) given at the 1992 ANS Winter Meeting at Chicago. The final thermal tests were done with mesitylene in the moderator chamber and with heating of the mesitylene.

The cold head and moderator chamber temperatures which were measured during cooling down without heating are shown in Fig. 5a. Figure 5b shows neon reservoir pressure changes due to cooling. The cold head temperatures reached 40 K after 125 min while there was no change observed in the moderator temperature. The cold head condenses neon which flows down the heat pipe to a point in the heat pipe where it is all evaporated. This liquid neon front works its way down the heat pipe until finally all of the heat pipe and the moderator chamber was cooled down at 480 min. From 480 to 540 min, further cooling condenses more neon as shown by the pressure variation, and decreases the temperatures to the final stable values.

Finally, the thermal performance of the TCNS was measured by applying 1-, 2-, 3-, 4-, and 5-W heat loads to an electrical heater attached to the moderator chamber. The power was adjusted and kept constant by controlling the current and voltage to the heater. The cold head and moderator stable temperature readings, stable neon pressure, and stabilization times for temperature and pressure for each heat load are listed in Table II. In general, the pressure stabilized more slowly than the temperature. The changes in these values were approximately exponential decay to stable values except for the 5-W moderator temperature which experienced an increase at 80 min and then continued to rise. The 1- and 2-W loads were handled satisfactorily by the neon heat pipe. The 3- and 4-W loads, while giving a larger neon pressure change, still were controlled in an acceptable manner. At 5-W, the moderator temperature did not stabilize, but the performance of the heat pipe was acceptable for short times of 1 or 2 hours.

We calculated that 2-W will be generated in the moderator by nuclear radiation during full power operation. Figure 6a shows the cold head and moderator chamber temperatures when the 2-W electrical heat load was applied to the moderator chamber. The neon reservoir pressure under the 2-W heat load is shown in Fig. 6b. Besides meeting the design specifications for cooling of the TCNS moderator, the neon heat pipe proved easy to use and gave stable temperature control. The self-regulating characteristics of this type of heat pipe (properly called a thermosiphon) are well known. Stability of the thermal system is an important consideration for the safe and reliable operation of the Texas Cold Neutron Source.

A Neutron Depth Profiling facility is being developed for use at a tangential beam port of the 1-MW TRIGA Mark II research reactor with funds from the State of Texas. The UT-NDP facility consists of a collimated thermal beam, a target chamber, a beam catcher, and necessary data acquisition and process electronics. The target chamber will be moved temporarily to the TCNS beam to try NDP measurements with focused cold neutrons.

A collimator system was designed and constructed for the UT-NDP facility to achieve a high quality thermal neutron beam with good intensity and minimum contamination of neutrons above thermal energies. Various single crystals were considered as filter to attenuate neutrons above thermal energies while allowing thermal neutrons to pass through with minimum attenuation.

A target chamber was constructed for the UT-NDP facility which can accommodate several small samples as well as a single large sample with a diameter up to 30.5 cm. This is accomplished by a fixture that can hold several small samples located in a circle or a single large sample. A stepping motor located inside the vacuum chamber rotates this fixture positioning the desired small sample in the beam or, combined with an up-and-down motion, selects any point on a large sample for analysis. The required up-and-down motion is controlled from outside the chamber by using a mechanical feed through.

A preprint of a transaction (attached) submitted for presentation at the ANS 1993 annual meeting in San Diego gives further details about the UT-NDP facility.

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Table I.

Design of 4-element converging guide

Length of each element: 20 cm
Focal point: 24 cm from the exit of focusing system
Focal area: 1 x 1 cm
Reflectivity: Measured data from Ovonics
Histories: 3,000,000
Neutron wavelength: 4 Å

Element	Entrance Height (mm)	Entrance Width (mm)	Slope (H)	Slope (W)
1	50.0	15.5	2.45 / 200	0.70 / 200
2	45.1	14.1	2.95 / 200	0.90 / 200
3	39.2	12.3	3.25 / 200	1.25 / 200
4	32.7	9.8	3.60 / 200	1.50 / 200
	25.5*	6.8*		

* Exit of element 4

Design of 8-element converging guide

Length of each element: 20 cm
Focal point: 24 cm from the exit of focusing system
Focal area: 1 x 1 cm
Reflectivity: Measured data from Ovonics
Histories: 30,000,000
Neutron wavelength: 4 Å

Element	Entrance Height (mm)	Entrance Width (mm)	Slope (H)	Slope (W)
1	50.0	15.5	1.10 / 200	0.00 / 200
2	47.8	15.5	1.30 / 200	0.00 / 200
3	45.2	15.5	1.50 / 200	0.10 / 200
4	42.2	15.3	1.70 / 200	0.20 / 200
5	38.8	14.9	1.90 / 200	0.40 / 200
6	35.0	14.1	2.20 / 200	0.70 / 200
7	30.6	12.7	2.50 / 200	1.20 / 200
8	25.6	10.3	2.50 / 200	1.70 / 200
	20.6*	6.9*		

* Exit of element 8

Table II. Measured thermal performance of the Texas Cold Neutron Source

Heat Load (1) (W)	Cold Head Temp (2) (K)	Moderator Chamber Temp (3) (K)	Temperature Stabilization Time(4) (min)	Neon Reservoir Pressure(5) (kPa)	Pressure Stabilization Time(4) (min)
1.0	29	30	5	35	5
2.0	31	32	30	59	40
3.0	32	35	50	129	75
4.0	35	39	120	315	180
5.0	37	up to 82 (6)	∞ (?)	540	200

(1) $\pm$ 0.05 W

(2) Silicon diode sensor , $\pm$ 2 K

(3) E type thermocouple, $\pm$ 3 K

(4) 95% of final value; heat load turned on with chamber cooled down

(5) $\pm$ 3 kPa

(6) at 300 min

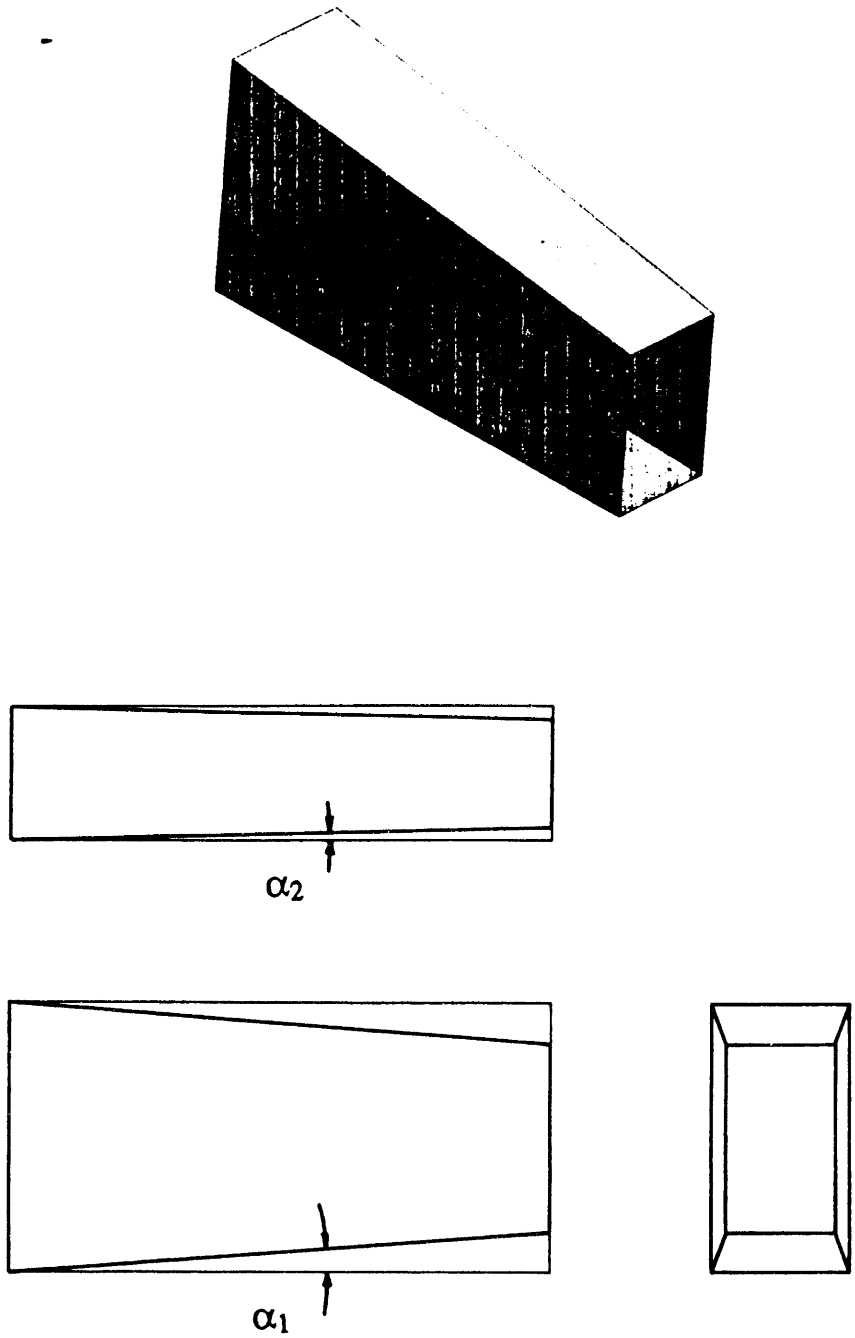


Fig. 1. Truncated rectangular cone section. The converging guide consists of several truncated rectangular cone sections each with different slant angles, α_1 and α_2.

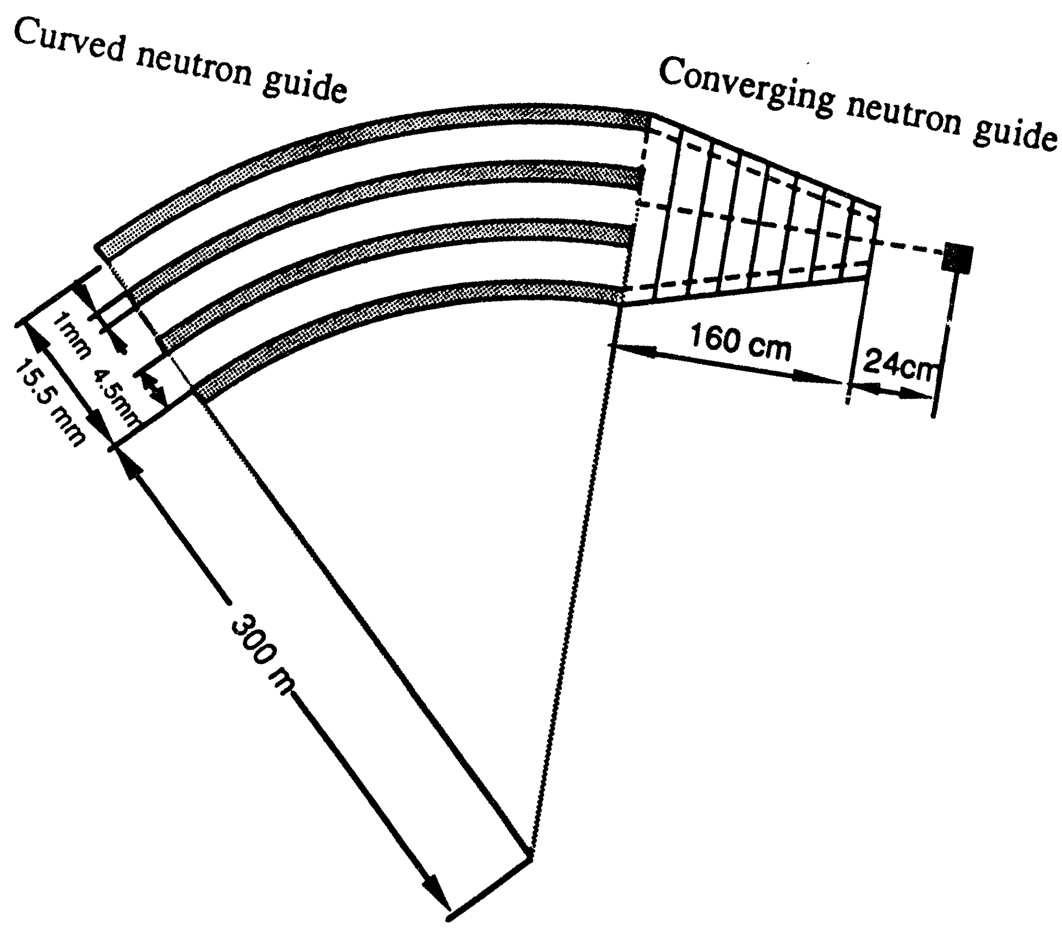


Fig. 2. Schematic top view of the three-channel curved neutron guide followed by the converging neutron guide. The length of the curved guide is 6 m and the height is 50 mm.

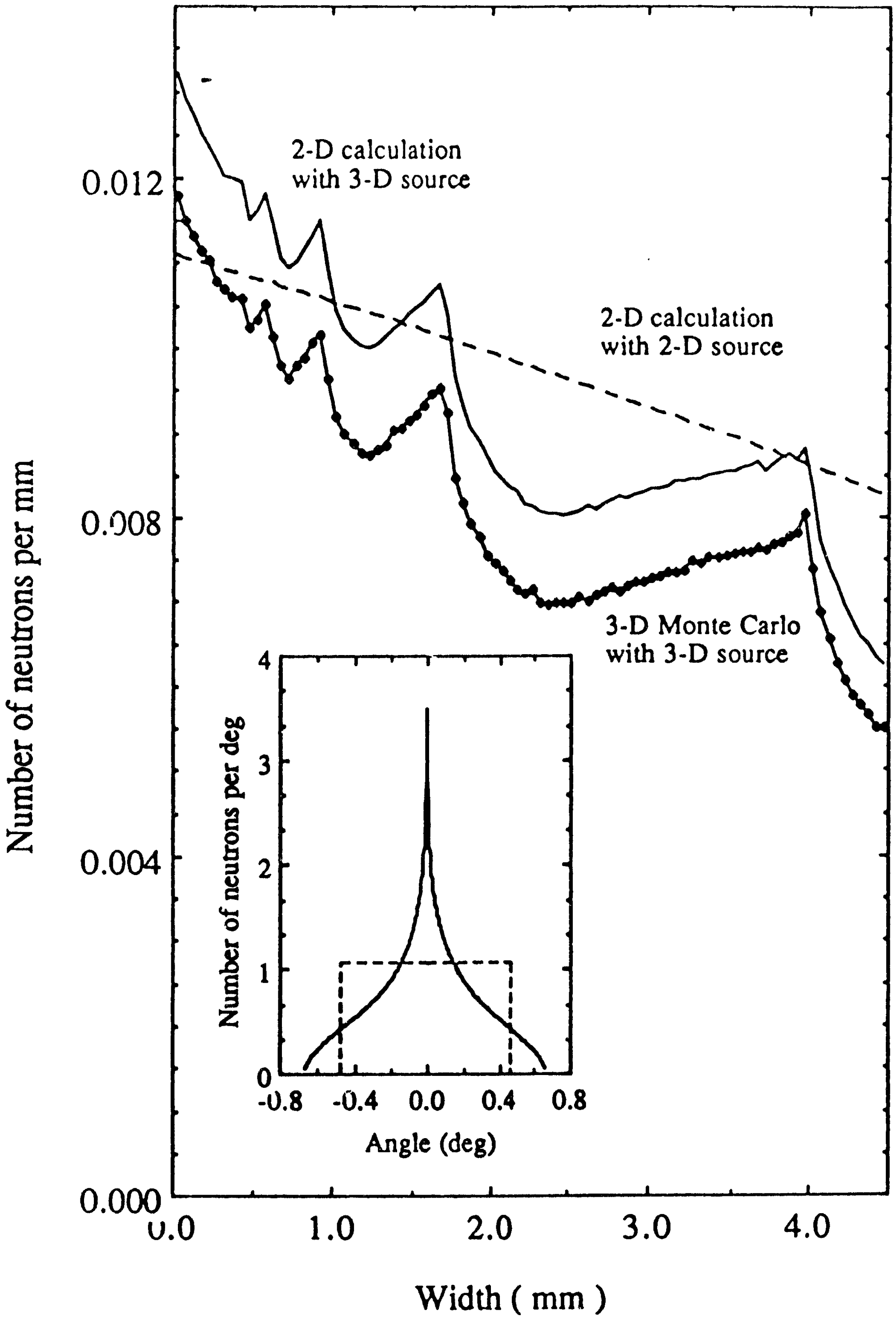
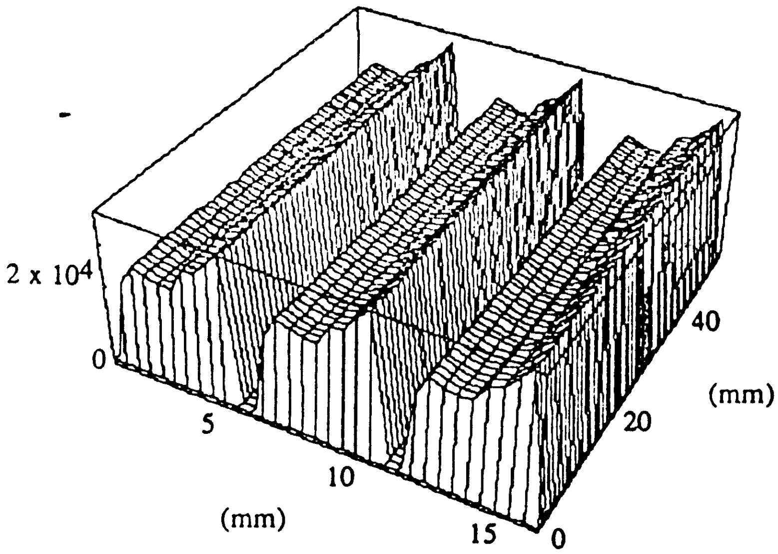
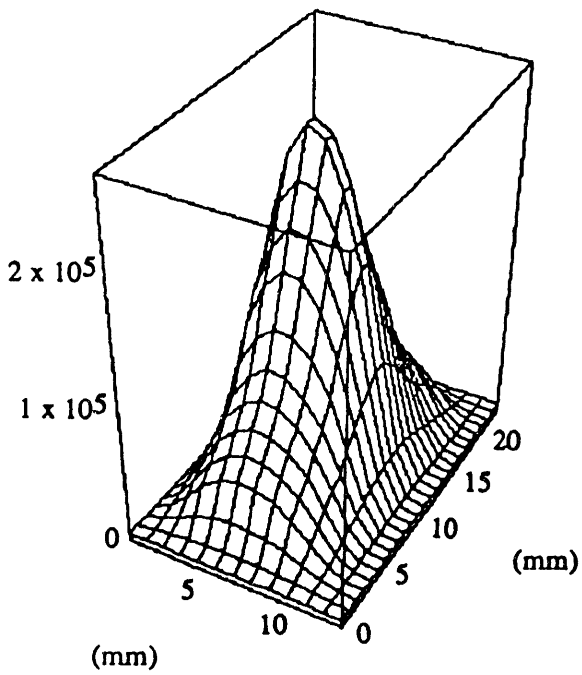


Fig. 3. Results of benchmark calculations. The dashed line represents a 2-D analytical calculation with a spatially uniform "isotropic-in-2D" source. The solid line, a 2-D analytical calculation with an "equivalent-3D" source. The line with points represents a 3-D Monte Carlo calculation with a spatially uniform isotropic-in-3D source.



(A) Neutrons entering converging guide



(B) Neutrons exiting at focal point

Fig. 4. Spatial distributions calculated for 4-Å neutrons entering the converging guide (A) and exiting the converging guide at the focal point (B). The z-axis is number of neutrons per mm^2.

Cooling

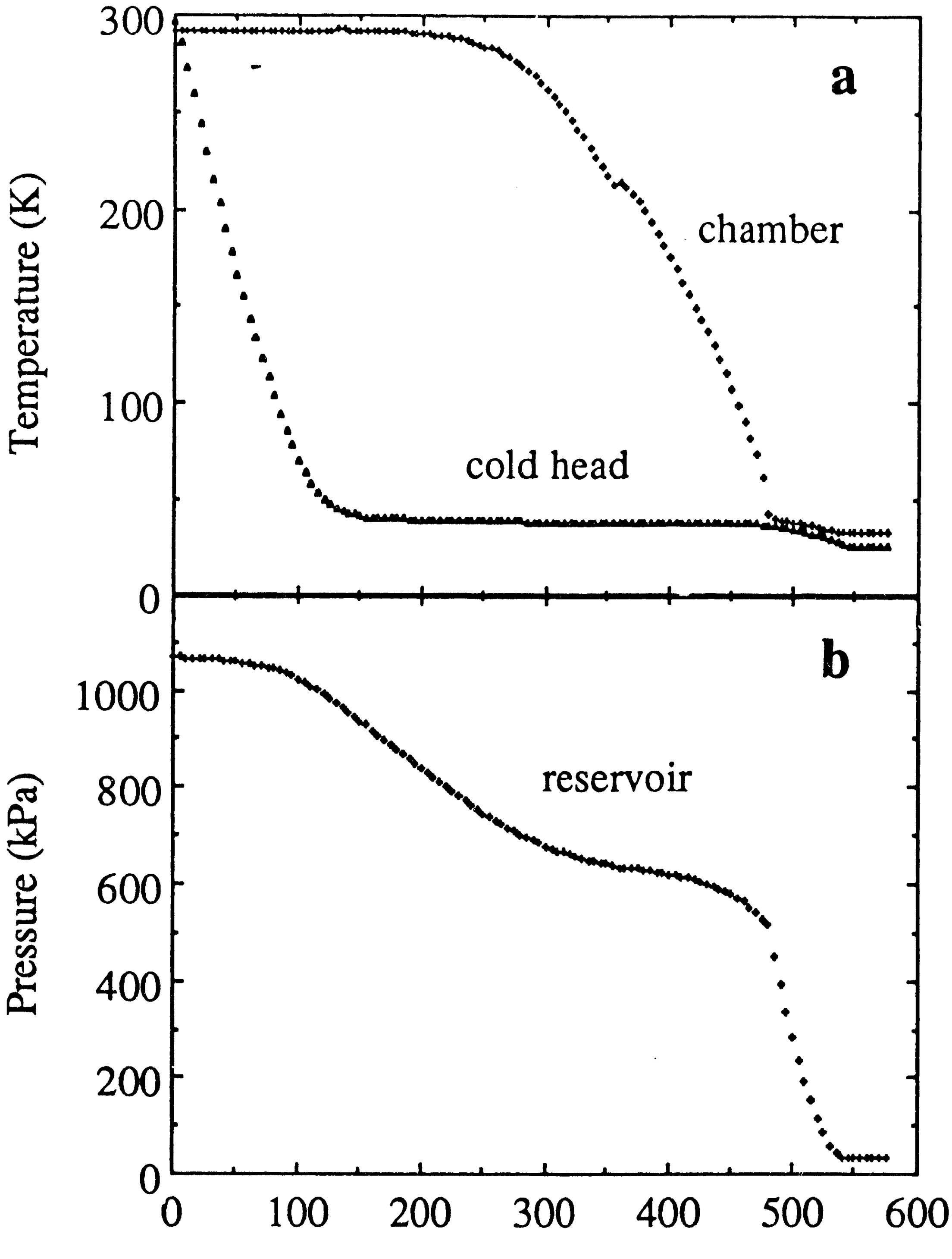


Fig. 5. Measured cold head and moderator chamber temperatures (a) and reservoir pressure (b) for the TCNS with an initial neon pressure of 1,095 kPa

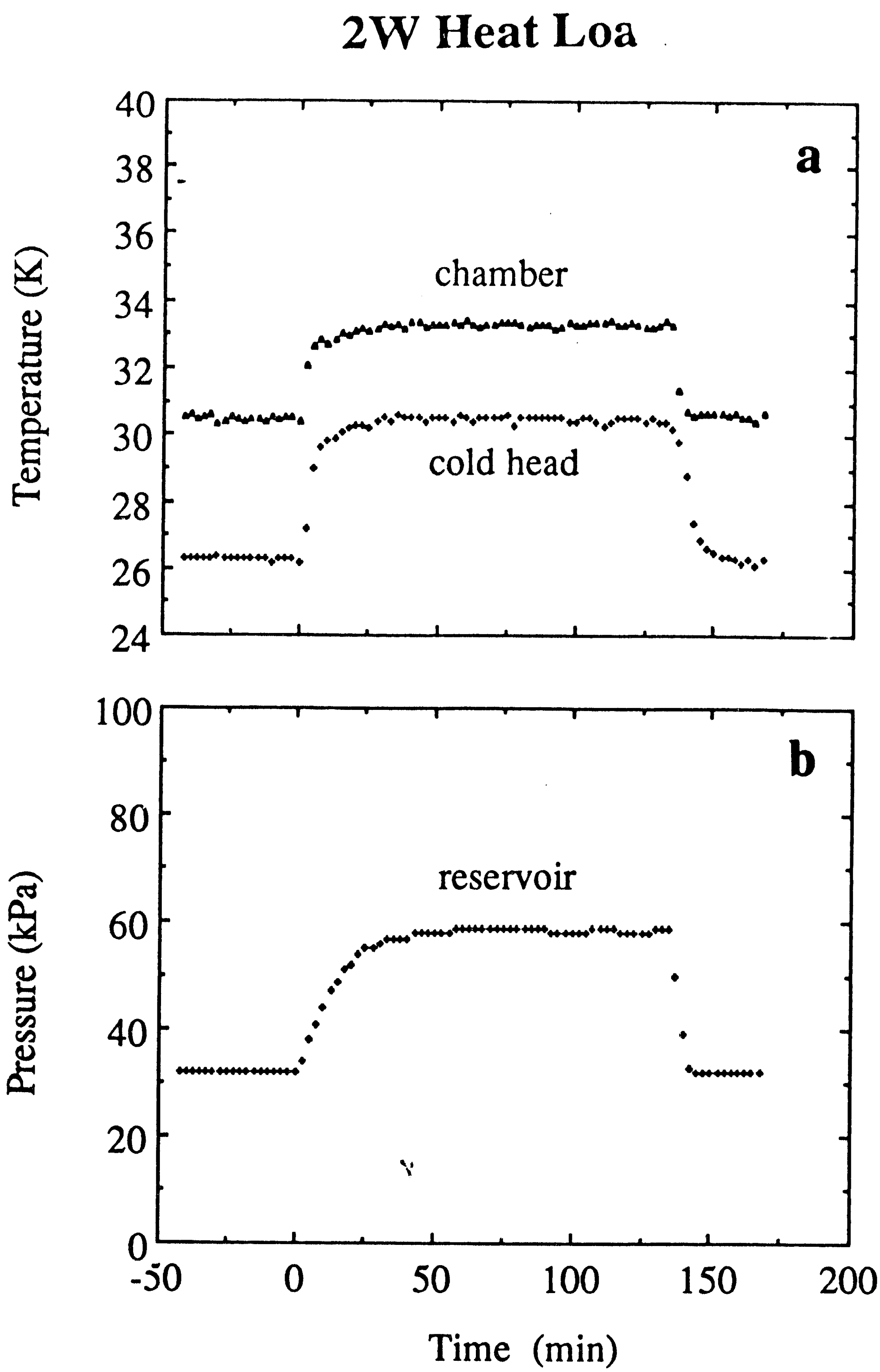


Fig. 6. Typical cold head and moderator chamber temperatures (a) and neon reservoir pressure changes (b) under 2-W heat load applied to TCNS moderator chamber

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