LA--12146-C

DE91 017559

*International Workshop
on Cold Neutron
Sources*

*March 5-8, 1990
Los Alamos, New Mexico USA*

*Compiled by
Gary J. Russell
Colin D. West*

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

*International Workshop
on Cold Neutron*

Sources

March 5-8, 1990

LANSCE

Los Alamos, New Mexico USA

cosponsored by

Los Alamos National Laboratory

Manuel Lujan, Jr.

Neutron Scattering Center, LANSCE and

Oak Ridge National Laboratory

Advanced Neutron Source, ANS

DO NOT MICROFILM
COVER

Los Alamos
NATIONAL LABORATORY

*Los Alamos National Laboratory is operated by the University of California for
the United States Department of Energy under contract W-7405-ENG-36.*

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

*Edited by Maria DiStravolo, LANSCE
Prepared by Teri Cordova, Paula Geisik,
Fin Kasik, Julie Martinez, Tatia Vander Maat, LANSCE, and
Gail Flower, Group IS-12*

*This work was supported by the US Department of Energy, Office
of Energy Research.*

An Affirmative Action/Equal Opportunity Employer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither The Regents of the University of California, the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by The Regents of the University of California, the United States Government, or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of The Regents of the University of California, the United States Government, or any agency thereof.

Session I

REVIEW PRESENTATIONS ON EXISTING COLD SOURCES:

(Design Criteria, Design Results, and Performance)

Chairman

Roger Pynn

CONTENTS

Abstract	
<i>Gary J. Russell/Colin D. West</i>	i

Introduction	
<i>Fred A. Morse</i>	v

Session 1 - Review Presentations on Existing Cold Sources (Design Criteria, Design, Results, and Performance)

Chairman: Roger Pynn

Neutronic Design of the ILL Cold Sources: An Historical Perspective	
<i>Paul Ageron</i>	1

The ILL Cold Sources	
<i>Klaus Gobrecht</i>	19

Cold Sources of the ORPHEE Reactor	
<i>Paul Breant</i>	31

The RISO Cold Neutron Source	
<i>Kurt N. Clausen</i>	57

The GKSS Cold Neutron Source	
<i>Wilfried Krull</i>	65

The Berlin Cold Neutron Source	
<i>Carl O. Fischer</i>	81

The Cold Neutron Source at the FRJ-2 in Jülich	
<i>Gunter S. Bauer</i>	91

Reactor Cold Sources in Japan	
<i>Masahiko Utsuro</i>	105

Existing Cold Sources at U.S. Reactors	
<i>J. Michael Rowe</i>	121

Cold Moderators for Pulsed Neutron Sources	
<i>Jack M. Carpenter</i>	131

Session 2 - Neutronics Calculation and Measurements

Chairman: J. Eric Lynn

Neutron Slowing Down and Thermalization	
<i>Valey F. Sears</i>	157

Historical Benchmarks and Experimental Problems <i>Peter A. Egelstaff</i>	179
Cold Moderator Scattering Kernels <i>Robert MacFarlane</i>	193
Cross-Section Libraries and Kerma Factors <i>Robert C. Little</i>	217
Monte Carlo Calculations for the CRNL Cold Neutron Source Design <i>Peter M. Brewster</i>	239

Session 3 - Cold Source Design Considerations (Part I)

Chairman: Bernard Farnoux

Some Remarks on Design Criteria and Optimization Concerns for Cold Neutron Sources <i>Gunter S. Bauer</i>	255
Heating Rates in Reactor and Spallation Cold Sources <i>Walter E. Fischer</i>	279
An Alternative in the Heat Transfer Design: A Cold Neutron Source Without Vacuum Insulation <i>Paul Ageron</i>	291
The ORNL Liquid Nitrogen Simulation Facility <i>Cliff C. Eberle</i>	299

Session 4 - Cold Source Design Considerations (Part II)

Chairman: Helmut Hoffman

Materials for Cold Neutron Sources: Cryogenic and Irradiation Effects <i>David Alexander</i>	321
Radiation Effects Concerns at a Spallation Source <i>Walter F. Sommer</i>	343
Instrumentation & Controls at Reactor Cold Neutron Source (Including Links to Reactor Controls) <i>Takeshi Kawai</i>	367
Hydrogen Safety <i>Wayne R. Frazer</i>	379
The Natural Convection Cooling with Vaporizing Deuterium for the Horizontally Arranged Cold Neutron Source of the HFR - Grenoble <i>Helmut Hoffman</i>	395

Session 5 - New Cold Source Proposals

Chairman: Tasso Springer

The Advanced Neutron Source (ANS) <i>Colin D. West</i>	409
Cold Source Design for the New Munich Reactor <i>Erich Steichele</i>	423
Status of the University of Missouri-Columbia Research Reactor Upgrade <i>J. Charles McKibben</i>	431
New Cold Source for ORPHEE Reactor <i>Paul Breant</i>	439
The Cold Neutron Moderator for the Continuous Spallation Neutron Source SINQ <i>Walter E. Fischer</i>	449
LANSCE Upgrade Cold Sources <i>Gary J. Russell</i>	471
A Design Concept for KENS-II Cold Neutron Source <i>Noboru Watanabe</i>	491

Session 6 - Wrap-up: What Have We Learned?

Chairman: Peter A. Egelstaff

Summary - Reactor Cold Sources <i>Colin D. West</i>	511
Cold Moderators at Pulsed Spallation Sources: A Personal View <i>Roger Pynn</i>	523
Some Concluding Remarks about Cold Moderator Development <i>Jack M. Carpenter</i>	529

Poster Session

Cold Neutron Source for the Present Munich Reactor <i>Ewald Krähling</i>	543
The Cold Neutron Multiplication of the Cold Neutron Source (CNS) at IAE, Beijing <i>An. Sun. Yu</i>	557
The Cornell University Cold Neutron Beam Facility Design Features <i>David D. Clark</i>	559
The LANSCE Target System <i>Gary J. Russell</i>	565

Evaluation and Validation of Neutron Cross-Sections for Liquid Hydrogen and Deuterium for the Design of Cold Neutron Sources <i>Wolfgang Bernnat</i>	575
Neutron Scattering and Transport Properties in Liquid H ₂ and D ₂ from a Synthetic Model <i>J. R. Granada</i>	587
Thermodynamic Performance Tests of the Cold Neutron Source at the Reactor KUR <i>Takeshi Kawai</i>	593
A Practical Approach to the Polymerization of Liquid Methane in a Cold Moderator <i>Trevor Lucas</i>	605
Appendix A Bibliography.....	613
Appendix B Questions Addressed.....	657
Appendix C Attendees.....	660

Abstract

Gary J. Russell
Los Alamos National Laboratory
Los Alamos, NM USA

Colin D. West
Oak Ridge National Laboratory
Oak Ridge, TN USA

The first meeting devoted to cold neutron sources was held at the Los Alamos National Laboratory on March 5-8, 1990. Cosponsored by Los Alamos and Oak Ridge National Laboratories, the meeting was organized as an International Workshop on Cold Neutron Sources and brought together experts in the field of cold-neutron-source design for reactors and spallation sources. Eighty-four people from seven countries attended. Because the meeting was the first of its kind in over forty years, much time was spent acquainting participants with past and planned activities at reactor and spallation facilities worldwide. As a result, the meeting had more of a conference flavor than one of a workshop.

As part of the workshop strategy, a list of questions to be addressed was sent to the participants before the meeting. A detailed list of the questions is given in Appendix B. The general topics covered at the workshop included

- Criteria for cold source design
- Neutronic predictions and performance
- Energy deposition and removal
- Engineering design, fabrication, and operation
- Material properties
- Radiation damage
- Instrumentation
- Safety

- Existing cold sources
- Future cold sources

The meeting began with review presentations on existing cold neutron sources, including design criteria, current design, and source performance. Calculational techniques for neutronic performance and available measurements on the neutronic performance of various sources were also covered on the first day. Design considerations for cold neutron sources, including optimization, heating rates and heat removal, materials properties, radiation damage and safety were covered on the second day. The third day was devoted to proposals for new cold neutron sources at both reactor and spallation facilities; this day also included a poster session and a tour of the LANSCE facility. The morning of the last day was devoted to summaries. Appendix A is a fairly extensive bibliography of work on cold neutron sources over the past forty years.

Here are some highlights of the items discussed at the meeting. Liquid deuterium and supercritical hydrogen appeared to be the favored choices for new cold neutron sources at reactors. Minimizing energy deposition in the walls of reactor cold-source containers could be an improvement that could affect the engineering design of cold neutron sources. Most attendees generally felt that neutronic gains at reactor cold sources will most likely come from more efficient coupling of the neutron source to the neutron-beam transport system rather than from improvements in cold source performance. The ability to change the moderating material viewed by a particular neutron spectrometer may be useful in some future applications. For reactors, an increase in neutron flux is always desirable if heat loads in the cold source are tolerable.

There are two types of spallation sources: steady state and pulsed. Design problems with cold neutron sources for steady-state spallation sources are analogous to those for reactors. Heat loads are similar, but the distribution between gamma-ray and neutron heating is different. Because of inherent lower-average heating rates in pulsed spallation sources, the possibility of using materials other than liquid hydrogen, such as liquid and solid methane, can be envisaged. To date, solid methane has only been used with proton currents of a few tens of microamperes, thus making it troublesome to employ it as a cold moderator at proton currents in the hundreds of microampere range. Also, because target-moderator-reflector systems for pulsed spallation sources tend to be undermoderated, substantial gains in neutronic performance may result by using composite and coupled cold moderators.

A general consensus reached at the meeting was that an important design feature for both reactor and spallation cold neutron sources is to get neutrons as cold as possible. Also, there is a real need

for better data on materials properties and the effects of radiation damage at cryogenic temperatures, which could be used to improve the design of cold neutron sources.

The meeting was deemed successful by all involved, and a follow-up meeting was proposed with the date and location to be decided later.

We want to take this opportunity to thank the following people who contributed so much to making the workshop a success. Jan Kapustinsky, Teri Cordova, and Paula Geisik worked very hard in helping to organize the workshop, and they, plus Kathy Rosenbalm (from ORNL), made the meeting run smoothly. Our thanks to Gail Flower and Dianne Hyer for their help in putting together the workshop literature. We appreciate the assistance of Tatia Vander Maat, Maria DiStravolo, Fin Kasik, and Julie Martinez in coordinating, typing, and proofreading the proceedings.

Gary J. Russell
Los Alamos Neutron Scattering Center
Los Alamos National Laboratory

Colin D. West
Advanced Neutron Source Project
Oak Ridge National Laboratory

Introduction

Fred A. Morse

Associate Director for Research
Los Alamos National Laboratory

Cold neutron moderators have been used at research reactors for many years, but it was only with the advent of the Institute Laue-Langevin (ILL) that such a source became a crucial element in the success of a facility. Even before its recent modernization program, the ILL cold source furnished neutrons to more than one third of their neutron spectrometers. And it has been these cold-neutron instruments that have been responsible for so much of the success which the ILL has enjoyed. It is not surprising, then, that cold sources have been retrofitted to existing research reactors around the world and that designers of new reactors, such as the planned Advanced Neutron Source (ANS), are convinced of the necessity of installing such a source. The interest in cold moderators at spallation neutron sources is a little different. Although the enhancement of cold-neutron fluxes is still an important consideration, even more crucial is the reduction of pulse widths which results from using the slowing-down rather than the moderated part of the neutron spectrum.

A great deal of technical and scientific knowledge about the functioning of cold moderators has been gathered at various institutions over the years but there seems to have been no natural vehicle for the sharing of the information. This workshop is intended to change that. It is quite natural that the ANS project and The Manuel Lujan, Jr. Neutron Scattering Center (LANSCE) should jointly organize this workshop. The ANS designers are faced with the daunting task of producing a cold moderator for a reactor that plans a higher flux than any other, and the LANSCE moderator upgrade in 1992 will enhance a facility which already has a higher peak flux than that of its competitors. Both of these plans call for the most advanced available concepts and technology.

It is also natural that this meeting on cold moderators should be held here in Los Alamos. The first measurements of scattering of slow neutrons by ortho- and para-hydrogen—results that form the basis for the use of hydrogen in cold moderators—were made here as part of the Manhattan Project and published in 1947. Since those days, liquid hydrogen has turned up in other Laboratory projects, from the first attempts to build a fusion bomb to rocket propulsion. Very often, we have observed technological developments that start in research, move into defense applications and then return, improved, to be used in support of basic research. This type of synergism is one of our main strengths at Los Alamos.

I would like to spend a couple of hours detailing a large number of our programs, but I know you are anxious to continue with your workshop. Therefore, let me conclude with a short description of Los Alamos so that you may have a better understanding of the talent you might draw upon here. We are principally an applied science and technology laboratory. However, we base these efforts on a \$200M/year basic research foundation. Our nuclear weapons program supports about half the Laboratory and includes a considerable amount of directed fundamental research in its own right, principally in materials. Approximately 25% of the Laboratory is supported by research and development for the Department of Defense. These programs are dominated by large hardware-intensive efforts with substantial industrial interaction. The other one quarter of the Laboratory is the basic research that I previously addressed. Our strengths lie in theory, computation, and interdisciplinary experimentation in the physical, chemical, and materials sciences. We have a solid engineering support brought about by the extraordinary engineering demands in our weapons programs. We choose to apply these talents to problems of national importance and scope. Hence, our vision of the Laboratory as a national resource to deal with scientific problems of national importance, especially those with national defense implications and/or dominated by a multidisciplinary nature. LANSCE, based at the Clinton P. Anderson Meson Physics Facility (LAMPF) proton accelerator, is just one example of our commitment to multidisciplinary research and our support for national facilities.

I wish you a successful workshop.

NOTICE

The papers published in these Proceedings were reproduced from camera-ready originals, furnished by the authors. No attempt was made to edit any of the contributions technically. The technical accuracy of the papers rests solely with the authors. No part of any paper may be reproduced in any form without the permission of the author. For the Question/Answer/Comment sections following the talks, the authors' corrected versions were used when available, otherwise our best interpretations are inserted.

Neutronic Design of The ILL Cold Sources An Historical Perspective

Paul Ageron

Institut Laue - Langevin
156X 38042 Grenoble Cedex, France

ABSTRACT

A brief history of the design of the cold sources of ILL (vertical VCS 1 and VCS 3 and horizontal HCN cold sources) and of the measurement of their performances is given below.

Before 1964

Two design directions

- Extrapolation to the ILL reactor of existing cold sources (small disk of liquid H₂): In high flux it was thought necessary to use annular vortex of liquid hydrogen in forced circulation.
- Feeling that deuterium in a large quantity was superior to hydrogen and could be far from the core (no vortex). Due to poor means of calculation (1 D Thermos code), experiment necessary to decide.

1964-1966

Experiments in the low flux reactor SILOETTE (100 Kw)^[1] main results

- Liquid hydrogen - effect of the vortex (Figure 1)
thickness 7, 15, 30 mm
- Deuterium, effect of diameter
18 cm, 38 cm, 38 cm + cavity (Figure 2)
- Decision: large D₂ source without hole (a proposal of gaseous hydrogen at 40 K and 10 bars without vacuum insulation was in the mean time rejected).

1972

First measurements by gold foils on the neutron guides

- Before and after the installation of VCS 1, guides H18-17 with only long wavelengths give a gain of about 70 instead of >150 measured in SILOETTE (effect of gradient).
- TOF spectrum measurement (later they will be checked by source + guide calculation).
(Figure 3A)

1977

First modernization program

- Improvement from VCS 1 to VCS 3
(cavity + vertical UCN guide)
- Creation of HCS
- Neutronic design made by calculation ^[2]
- Young & Koppel model for cross section (modified by UTSURO for D₂)
- Geometry in the reactor

- D₂O cylinder with source and albedo adjusted to reproduce the flux gradient on the z-axis (Figure 4)
- Use of DOT III 2D 15 groups of energy transport code

Results

- For VCS 3 and VCS 1: comparison of brightness spectra without and with cavity (outside and inside) (Figure 5)
- This calculation has been made also by Montecarlo 3D TRIPOLI: poor statistic for the brightness, but good indication for the flux in front of the vertical VCN guide (Figure 3B)
- For HCS (disk with a diameter <21 cm)
 - Deuterium (optimum about 20 cm thick). Comparison with large source (Figure 7)
 - Hydrogen (optimum about 5 cm thick). Comparison with existing sources (Figure 6)
 - Calculation confirm the better efficiency of normal H₂ compared to ortho H₂. In the same geometry comparison of D₂ and H₂ flux at the emitting surface for D₂ and H₂ at 1.8 Å (thermal) 5.6 Å (cold)
 - The H₂ source is more homogeneous than the D₂ one, but at the same level in the center (Figure 8)
 - Finally, the D₂ source was chosen for reasons of technology and of reactivity. Comparison with VCS 3 and 1 in Fig. 5 - effect of additions of H₂ in D₂ optimum at 10% (gain: 1.2) (Figure 9)

These calculations give also the capture rate in the structure for the calculation of the nuclear heating.

1985

Measurements at the start up of VCS 3

- Gain by a factor 1.7 for $4 < \lambda < 6 \text{ \AA}$ for instruments on the cold guide H15
- On the vertical guide
- Without turbine: UCN density and flux VCN spectra
- With turbine: VCN density and spectra^{[4], [5]}

1987-1988

Measurement at the start up of HCS

- Direct brightness spectrum measurement (without guide), in agreement with the calculated one (Figure 10).
- The Beryllium filtered cold neutron brightness has been used to control the correct level of the cold moderator.
- Measurement of the flux spectrum on a guide on HCS with 58 Ni coating, compared to a similar guide, with natural Ni coating, on the VCS 1 and on VCS 3 with the cavity improvement (Figure 11).
- The angular profile of the flux after a guide on HSC have a $\text{FWHM}_{\text{radian}} = 3 \cdot 10^{-3} \lambda \text{ \AA}$ (Figure 12).

CONCLUSION

From these different calculations/measurements, which are in good agreement with D₂ sources in the ILL Reactor, one can conclude:

- A "small" D₂ source in a mean flux of $8 \cdot 10^{14} \text{ n cm}^{-2} \text{ s}^{-1}$ has the same brightness as a large D₂ source in a mean flux 2 times lower.

- A significant improvement of the cold neutron flux is to be expected, no longer from the source, but from the transmission system: guide with improved coating and/or focusing systems.

REFERENCES

1. H. S. Harig, Etude de Sources de Neutrons Froids à Hydrogène et Deuterium Liquides, Thèse Université Grenoble, (1967).
2. P. Ageron, Special Neutron Sources, Symp. on Neutrons Scattering in the nineties, Jan. 14-18, 1985, IAEA Vienna, (1985).
3. P. Ageron, Cold Neutron Sources at ILL, Nucl. Inst. Methods A 289 (1989) 197-199.
4. A. Steyerl, S. S. Malik, Sources of Ultra Cold Neutrons, Nucl. Inst. Methods A284, (1989) 200-207.
5. A. Steyerl and Al, "A New Source of Cold and Ultra Cold Neutrons," Phys. Letters A Vol 116, N7, (1986) 347-352.

Figure 1 Measured spectra from annular sources of normal hydrogen with thickness 1: 30 mm, 2:15 mm, 3:7 mm, 4:D₂O (reference)

Figure 2 Measured spectra from cylindrical sources of deuterium with diameters: 380 mm, 1: with 2 without cavity; 3:180 mm 4: D_2O (reference)

Figure 3 A: TOF measurement of the flux spectrum at the end of a guide on VCS 1
 B: Gain over VCS 1 for:
 • : HCS, cavity 0 : measured in Siloette,
 + : transport, x : Monte Carlo calculation

Figure 4 Geometries for R, Z calculations of VCS 1 and 3 and HCS; neutron sources position and albedo values used for reproducing the unperturbed flux along the axis.

Figure 5 Calculated brightness of:
 • : HCS ($D = 18 \text{ cm}$), X : VCS 1 ($D = 38 \text{ cm}$), VCS 3 ($D = 38 \text{ cm}$)
 o : outside, + : inside the cavity

Figure 6 Calculated gain for HCS ($D = 18$ cm) : hydrogen 5 cm thick:
 ▽ : normal, Δ : para, + : deuterium 17 cm thick. Comparison with measurements in
 existing hydrogen sources.

Figure 7 Calculated gain for deuterium sources + : large D = 38 cm o : small D = 18 cm, comparison with measurements in Siloette.

Figure 8 Calculated thermal and cold flux profiles for — : Deuterium (17 cm thick) and --- : normal hydrogen (5 cm thick)

Figure 9 Calculated gain, versus the neutron wavelength for an optimum (10%) hydrogen addition in the deuterium HCS; a : average, c : center

Figure 10 Comparison of --- : calculated and— : measured brightness spectra of HCS

Figure 11 Measured flux spectra after neutron guides on 1 : VCS 1, 2 : VCS 3 (cavity), 3 HCS

Figure 12 Measured angular profiles of the flux at the end of a guide on HCS at wavelengths: Δ : 5Å, • : 7Å, x : 10Å, + : 15Å, o : 20Å.

The ILL Cold Sources

Klaus Gobrecht

Institut Max von Laue - Paul Langevin
156 X - 38042 Grenoble Cedex - France

ABSTRACT

The design criteria, design, fabrication, operation, safety, instrumentation, and performance of the two cold sources at the high flux reactor are briefly described.

I. INTRODUCTION

It is clear today that slow (cold) neutrons are an important tool in research, and that cold (i.e. refrigerated) moderators are the only way to get these in sufficient quantities. Therefore neutron sources for research should have at least one cold neutron source (CNS), either foreseen from the beginning or backfitted later. The High Flux Reactor of the Institut Laue-Langevin (ILL) experienced both cases and has today two functioning CNS, which, we believe, represent optimal design and performance.

II. DESIGN CRITERIA

1. Moderator Medium and Phase

Deuterium is nearly the ideal moderator substance for cold neutrons; it has the following favourable properties:

- small neutron absorption cross-section (0.52 mb for thermal neutrons),
- small interaction with other (α, β, γ) nuclear radiation,
- stable under radiation,

- contains only light nuclei,
- is a dense, but not viscous fluid at low temperatures.

Its drawbacks are a relatively low scattering cross-section (7.64 b for thermal neutrons) which means an important neutron mean free path and consequently big moderator volumes, and a relatively high boiling temperature which limits its use to temperatures above about 20 K if, as at ILL, it is used in its liquid and gaseous state.

2. Heat Removal

Of the two options:

- bringing the refrigerant to the moderator volume,
 - having the heat brought by the moderator fluid to the refrigerant,
- we have chosen the latter, the former one means a lot of extra hardware (and nuclear heating) in, or around, the moderator volume.

In both ILL CNS the deuterium is condensed in a He-gas cooled heat-exchanger several meters away, and above the moderator volume. The liquid flows down to the moderator volume where it takes up heat by evaporation. The vapor flows up to the condenser - heat-exchanger for condensation. This free convection scheme is called a 'two-phase thermal syphon' and works like a gravitational heat pipe. It has the advantage of using no moving parts in the deuterium circuit. It is isothermal and therefore limits the confinement of the deuterium to a single concentric tube (Fig. 1). There is an important cooling power reserve in the circulation rate: the upstreaming fluid can be either pure vapor or two-phase fluid, in which the vapor bubbles work as pistons, driving the excess liquid around. This so-called 'bubble pump' principle is fully exploited in the second (horizontal) ILL CNS.

Details are given by Hoffmann (1).

3. Cold Neutron Flux Optimization

Ideally, the moderator volume is situated in the maximum thermal neutron flux and has linear dimensions of several mean-free path lengths. In High Flux Reactors there is interference between the highest possible flux and the heat removal capacities. If the moderator volume is large and situated in a flux gradient, the brilliance of the source can be increased by a reentrant hole in the volume, as has been realized in our vertical CNS (2). The same brilliance can be obtained with a smaller volume (having a smaller heat load but some under-moderation) placed closer to the flux maximum. This option has been used in the ILL horizontal CNS.

Fig. 1. The ILL vertical cold neutron source principle
M: Moderator volume, G: Separation of vacuum systems, V: Deuterium vapour at 25 K,
L: Liquid deuterium at 25 K, C: Condensing surface, P: Pumping line, H: Cold He inlet

III. DESIGN

The first cold source, called the Vertical Cold Source, contained in a vertical thimble made of zircalloy, was built at the same time as the reactor. Initially, it was a spherical aluminum cell with a diameter of 380 mm and a thickness of 1.5 mm, and was filled with liquid deuterium. In 1985, it was modified in two ways:

- i) a cavity was installed made of a 0.8 mm magnesium sheet, 100 mm large, 200 mm high, 260 mm long, filled with gaseous deuterium, which enhanced the flux in the direction of the horizontal neutron guides;
- ii) The vertical service tube was enlarged in order to instal a vertical neutron guide down to the moderator.

It contains about 20 l of liquid deuterium; its centre is at 70 cm from the reactor axis, where the unperturbed neutron flux is about $4.6 \times 10^{14} \text{ n cm}^{-2} \text{ s}^{-1}$. The total nuclear heating is presently about 6 kW (4.5 kW before the modifications).

Fig. 2. The ILL horizontal cold neutron source (in-pile parts).
1: Beam tube, 2: Beam tube liner, 3: Moderator volume, 4: Shielding plug,
5: Nickel neutron guide tubes, 6: Shielding plate, 7: Beam shutter, 8: Safety valve,
9: Thermal syphon, 10: Glass neutron guides, 11: Condenser

The second cold source, called the Horizontal Cold Source, was installed in 1987 inside a 10" horizontal beam tube, made of zircalloy. It is an aluminum cylinder (diameter: 210 mm; thickness: 2 mm) with two elliptical domes (maximum length of the cell: 210 mm). It contains about 6 l of liquid deuterium, its centre is at 55 cm from the reactor axis, where the unperturbed neutron flux is about $8 \times 10^{14} \text{ n cm}^{-2} \text{ s}^{-1}$. The total nuclear heating is about 3 kW (Fig. 2).

Each CNS has its own deuterium circuit with condenser and gas buffer volume (Fig. 3). The condensers are cooled from one 10 kW Brayton cycle helium refrigerator having two "Air Liquide" turbines and one 700 kW screw compressor. The cryogenics is resumed in Table 1 (see also (3)).

Fig. 3. Schematic view of the horizontal (full lines) and the vertical (dashed lines) cold neutron sources

B: Reactor block, C: Reactor core, R: Reflector, M: Moderator volume,
 DDG: Beam tube, TH: Thermal syphon, EC: Heat-exchanger/condenser,
 GB: Gas buffer volume, COMP: Compressor, REFRI: Refrigerator,
 NG: Neutron guide tubes to the experiments

TABLE I
CHARACTERISTICS OF THE ILL CNS

	Vertical CNS		Horizontal CNS	
Moderator	liquid deuterium			
Cell volume	25	l	6	l
Cell diameter	380	mm	210	mm
Cell weight	< 2	kg	1	kg
Cell material	Al + Mg		Al	
Working temperature	25	K	25	K
Working pressure	150	kPa	150	kPa
Pressure limit	1	MPa	1	MPa
Heat load	6.5	kW	3	kW
Maximum heat flow	1	W/cm ²	1	W/cm ²
Deuterium mass	10	kg	3.2	kg
Evaporation rate	20	g/s	10	g/s
Circulation rate	20	g/s	> 20	g/s
Circulation model	heat pipe		bubble pump	
Length of transfer line	8	m	8	m
Condenser	tubular		compact plate	
He throughput	190	g/s	130	g/s
Buffer volume	18	m ³	6	m ³

IV. FABRICATION

Although it is possible today to buy a custom-made turn-key CNS from industry, ILL prefers to play the role of an industrial architect who specifies and orders components from specialised and competent workshops. The reasons for this are

- i) preliminary feasibility studies with test runs, full scale mock-ups, etc. created an important know-how inhouse;

- ii) trouble shooting, servicing and replacement is much easier if components are designed and assembled inhouse;
- iii) finally: the responsibility for the CNS installations so close to a nuclear facility demands much inhouse competence which can best be obtained by being closely involved in the construction.

All in pile parts were specified by ILL and ordered outside to be built following a severe quality assurance scheme. Same for other non standard parts, except for material specifications, which were less severe. Standard components like the refrigerator or vacuum pumps were bought accepting the suppliers quality assurance. Assembly and tests were carried out by the ILL services, who now supervise and service the CNS.

V. OPERATION

The CNS operation is closely connected with the reactor operation. There is no emergency cooling of the in-pile parts, which means, that the reactor power has to be reduced when the CNS cooling power becomes too low, and the reactor is shut down (Scram), when the refrigerator fails for more than one minute. The Scram is a nuisance because of the xenon poisoning of the reactor core, which holds the reactor down for 48 hours. The high MTBF of the refrigerator and the existence of back-up compressors, however, reduce perturbations to less than 1 % of the reactor operation time ⁽⁴⁾. The deuterium condensation rates in each CNS are adjusted individually to the required cooling power by injecting of warm He-gas into the He-circuit of each heat exchanger. The cooling power is monitored by measuring the temperature in the deuterium loop (via the vapor pressure).

After each reactor cycle, which lasts 45 days, the CNS are warmed up and a deuterium inventory and oxygen analysis are performed. Initial traces of oxygen from added deuterium seem to disappear by inverse radiolysis (forming traces of heavy water).

VI. SAFETY

Safety analysis is common to all CNS. The main risks are

- i) chemical (due to the presence or formation of inflammable gases),
- ii) cryogenic (due to the presence of cold fluids and surfaces),
- iii) nuclear (due to the possibility of sudden reactivity changes, possible in a nuclear reactor only).

1. Chemical Risks

In the ILL CNS the formation of inflammable deuterium-air mixtures is excluded by the following safety concepts:

- triple containment of the deuterium circuits throughout, together with an inert gas envelope (or water);
- continuous leak checking in the cryogenic vacuum and inert gas liners;
- computer controlled gas handling with numerous interlocks;
- all deuterium containing components are protected by concrete or steel structures.

The very improbable event of a complete rupture of a deuterium duct could eventually lead to the build-up of an explosive deuterium-air mixture inside the CNS. In this case at least one barrier of the triple containment is strong enough to withstand the overpressure of a subsequent explosion.

One problem should not be neglected: the accidental release of irradiated deuterium, which contains some tritium, into the atmosphere. In the ILL CNS the bursting discs of the deuterium circuit and the vacuum liner are set to such a high bursting pressure that deuterium should normally stay confined in the installation.

2. Cryogenic Risks

If the temperature control of the deuterium circuit fails, deuterium may freeze and block the circuit, leading to a pressure build-up in the moderator cell which may eventually burst. The outflowing boiling deuterium creates high strain on the zircalloy thimbles and high overpressure in the cryo-vacuum. The consequences of this accident have been studied, calculated and simulated, and the thimbles were designed to limit the heat transfer and pressure build-up, and the vacuum tubes are dimensioned in order to cope with the amount of evaporated deuterium.

Small leaks of inert gas (nitrogen) or water are difficult to detect in the cryo-vacuum because of cryopumping of the cold surfaces. But calculations and tests showed that one needs such big quantities of nitrogen or water, that the leaks manifest themselves indirectly, before there is any danger for the installation.

The use of helium as inert gas has been rejected for the reason that, although not condensable, it cannot be distinguished from deuterium with an ordinary leak detector or mass spectrometer.

3. Nuclear Risks

Here only the reactivity change in the vicinity of the reactor core due to filling or emptying of the moderator volumes have to be taken into account. The ILL CNS are sufficiently far away from the neutron flux maximum, that the effect has been found to be marginal.

VII. INSTRUMENTATION

1. Refrigerator

The refrigerator is of a standard industrial design, and its instrumentation is straight forward. Only the automatic switch-over from the main compressor to the two back-up compressors in case of failure of the former, is worthwhile to be mentioned, since it uses modern redundant programmable controllers.

2. Gas Handling

No gas handling is possible while the reactor is running. Semi automatic gas handling like refilling, analysis, etc. means that the manipulations are done by the technical staff but controlled by the computer. There is no on-line cold-trap and no on-line oxygen monitor, but gas bottles are analysed twice before use.

3. Operation and Safety Instrumentation

During operation the deuterium pressure is the only process variable. It is kept constant at 150 kPa, which corresponds to a temperature of 25 K in the moderator cell and loop, by injection of warm helium (process) gas into the cold end of the condenser (Fig. 4).

Important deviations to one or the other side of this pressure shut the refrigerator down, and the reactor.

Poor cryo-vacuum or small pressure excursions in the inert gas liner give alarms to the reactor control room.

A pressure higher than 5 kPa in the cryo-vacuum or large pressure excursions in the inert gas liner shut the refrigerator down, and the reactor.

Fig. 4. Schematic diagram of the refrigeration circuit.
 HP: High pressure line, BP: Low pressure line, BOITE FROIDE: Cold box,
 TURBINES DE DETENTE: Expansion turbines,
 REGULATION DE LA S.F.H.: Horizontal CNS temperature control,
 LIGNES FROIDES: Cryogenic vacuum insulated pipes,
 CONDENSEUR DE LA S.F.H.: Horizontal CNS condenser - heat-exchanger,
 CONDENSEUR DE LA S.F.V.: Vertical CNS condenser

VIII. PERFORMANCE

The neutronics (spectra, flux gain, brightness, etc.) is given in (2).

In spite of the direct interaction of the CNS on the reactor operation (any failure in one CNS shuts the reactor down), less than 1 % (including xenon poisoning) of the now more than 25 000 reactor days were lost due to CNS malfunctioning.

Today about 30 instruments on 10 guides use cold or ultra-cold neutrons at ILL, and projects are underway to add further cold neutron guides to the existing CNS.

IX. ACKNOWLEDGEMENTS

I wish to thank P. Ageron and J.M. Astruc for the fruitful discussions we had together, and D.A. Wheeler for reading the manuscript.

X. REFERENCES

1. H. Hoffmann, "Thermal -Hydraulic Calculations and Measurements", these proceedings.
2. P. Ageron, "Cold Neutron Sources at ILL", Nucl. Instrum. Methods, **A284**, 197 (1989).
3. J.M. Astruc and K. Gobrecht, "Cryogenics of Cold Neutron Sources"; Proceedings of the XVIIth International Congress of Refrigeration, Vienna, 1987, vol. F, p. 111.
4. J.M. Astruc and G.M. Gistau, "Analysis of the Reliability of the Refrigeration System used in the Reactor Cold Source at the ILL, Grenoble, after 11 Years of Operation", Proceedings of the Tenth International Cryogenic Engineering Conference (ICEC 10), Helsinki, 1984, (Butterworth ed.), p. 566.

The ILL Cold Sources

Klaus Gobrecht

Questions/Answers/Comments

(H-J. Roegler)

Question:

To me your expression "Triple Containment" is somewhat misleading, since the liquid cold sources do not have triple containment throughout as in the supercritical cold sources. Can you please comment on that?

Answer:

You are right if you define "triple containment" by three solid walls between the moderator fluid and the ambient air. At the ILL vertical cold source, we have three barriers, with the outermost barrier being the several meters deep pool water.

The ILL horizontal cold source has true triple containment.

Neither of the cold sources have triple containment in parts of the system wherever the moderator fluid is warm. Here, we only have a double containment (like supercritical cold sources).

(T. Springer)

Question:

I refer to Ageron's remark on source luminosity and flux, which one can extract. In order to use the full solid angle of a neutron guide at large wavelengths, the guide must start as close to the source as possible. How close has one gone, and how close could one hope to go?

Answer:

Our vertical guide for ultra cold neutrons starts right at the edge of the liquid moderator (liquid deuterium) by which it is cooled. The guide on the horizontal cold source starts at 216 cm from the rear face of the moderator chamber. This distance is optimized for a 12 x 12-cm² guide made of pure Ni with ⁵⁸Ni coating. Ni on glass or multilayer guides without forced cooling have to start even further away.

Cold sources of the Orphée reactor

P. Breant - B. Farnoux - J. Verdier

Commissariat à l'Energie Atomique
FRANCE

PART ONE CURRENT SITUATION

ABSTRACT

This report examines the design and operating mode of the cold sources currently used in ORPHEE. A brief analysis of safety, and a report on examinations after irradiations of a stainless steel hydrogen cell removed from the reactor in 1987 is given.

ORPHEE has two vertical cold sources SF1 and SF2 located in the thimbles in the heavy water reflector and approximately 30 cm from the reactor core centre.

These cold sources have a non perturbed thermal flux of around $2.5 \cdot 10^{14} \text{ n.cm}^{-2}.\text{s}^{-1}$ and a gamma flux of around 0.7 to 0.8 w/g.

The vertical setup as from the pool enables separating the technological constraints associated with the operation of these two sources, from those which result from the actual needs of the researchers and experiment managers who use the beams in the reactor hall, therefore, in an independent zone (see figure 1).

The sources provide cold neutrons to six main guides and two secondary guides (a third secondary guide is possible) and an equipment located in the reactor hall, which enables setting up two 3-axis spectrometers.

The six guides and their secondary guides are situated in a vast 50 m long by 30 m wide laboratory (the guide hall) (see figure 2). Fourteen spectrometers of various kinds are currently installed there.

I. DESIGN AND STUDY BASIS

The cold sources were designed and studied based on experience acquired during construction of the cold source of the high flux reactor (Institute Laue-Langevin, Grenoble). All the hydrogen circuits were located inside the pool, which defines the safety category, quality level and dimensioning constraints.

In addition, the cold sources were designed to function with the reactor in operation, either refrigerated, i.e. with liquid hydrogen, or not refrigerated; this latter type of operation imposed the choice of materials and performances to be reached.

It is important to note that the safety of the equipment in the reactor in the event of accidental rupture of the hydrogen circuit rests wholly on the mechanical strength of the bottom of the source, and particularly the thimble. This setup was chosen to counter the fact that it is impossible to maintain the working conditions of the cell structures in strict accordance with the usual mechanical practices (for example, ASME code).

However, the same care was taken and same manufacturing conditions used for the cell as for an item in safety category and quality 1. Particular emphasis was laid on verification of the cold mechanical characteristics and on assessment of these same characteristics when hot, for control purposes.

II. NEUTRON SPECTRUM AND NUCLEAR HEATING

Boiling hydrogen was chosen as a moderator. It is contained in an envelope that has a horizontal cross-section of an ellipse (flask shape).

This envelope has the sole function of limiting the cold source geometrically; the function of the envelope in terms of safety is provided by the aluminium-magnesium alloy thimble which penetrates into the heavy water tank.

The thermalized neutrons' spectrum is barely modified by

- the thin wall (0.8 mm) of the hydrogen cell (A286 steel),
- the thimble wall (6 mm),
- the heavy water layer contained between this thimble and the channel ends. Its thickness is from 0.5 to 2 mm thick.

At the source locations, heating is approximately 600 watts (0.7 w.g^{-1} in the metal).

This thermal energy is evacuated by the helium refrigerator; available power: 700 watts on each loop.

When operating with a nonrefrigerated source, the heat is evacuated by radiation and conduction in the gas filling the thimble. The vacuum chamber is filled with helium at low pressure, to improve the exchanges, the cell temperature does not exceed 350°C .

The nuclear heating of the thimble is evacuated by the heavy water circulating in the reflector tank. The thermal gradient in the wall is only 12°C .

III. DESCRIPTION

The two cold sources consist of :

- two totally independent hydrogen loops immersed in the pool (figure 3),
- one common cryogenerator using helium as the heat remover (figure 4),
- one control system,
- the circuits conditioning equipment.

III.1 Hydrogen loops

Each of the two hydrogen loops fully immersed in the reactor pool comprises

1) One part under flux or source bottom consisting essentially of

- a cell containing liquid hydrogen,
- a thimble penetrating across the top tube system in the reflector tank,
- an annular thimble penetrating the outer thimble up to the top level of the tank and forming the light water protection.

The cell is in high strength nickel-chrome (A286 - American reference, ATVSMO - Creusot Loire reference). It is in the shape of a flask 105 mm high, 130 mm wide and 50 mm thick, with a wall thickness of 0.8 mm. Capacity is approximately 750 cm³. It is prolonged by a tube of the same nature 25 x 23.4 mm over an approximate length of 850 mm, which connects it to the thimble. Its mass added to that of the tube is approximately 800 g.

The aluminium-magnesium alloy thimble (AG3 NET) has an internal diameter of 138 mm and a thickness of 6 mm at the flask.

The bottom of the source is linked to the condenser located in the light water around the pool by a cryogenic line.

The hydrogen loop vacuum chamber is made up of the thimble, the walls of the inner thimble, the envelope of the hydrogen cryogenic line and the condenser envelope.

2) Condenser

This is a Z2CN18-10 stainless steel tubular exchanger where the helium loses its heat by liquefying the hydrogen.

The helium circulates from bottom to top in counter flow to the hydrogen gas to be condensed, which arrives through a central channel in the top section. The hydrogen condenses inside the tubes and is collected in the bottom part in a small volume annular space from which leaves the liquid transfer tube. The connection tube to the hydrogen buffer tank arrives at the top.

The exchange surfaces are designed to condense the quantity of hydrogen evaporated by a thermal power of 700 watts, at an absolute pressure of between 1 to 2 bars.

This device is contained in a vacuum chamber welded to the hydrogen cryogenic line (link between condenser and source bottom) and to the link tube with the hydrogen buffer tank.

After testing, the cryopump of insufficient yield located in the top part of the condenser was doubled by a cryopump of capacity 5 litres TPN of hydrogen up to 10⁻⁴ mbar and with a pumping speed of over 400 l.s⁻¹ at 10⁻⁵ mbar. The new cryopumps were placed at each condenser intake on the cold helium pipe coming from the turbines (after the joint of the

helium cryogenic line). They maintain a secondary vacuum of $< 10^{-5}$ mbar in the chambers containing the cold parts of the hydrogen loop.

This envelope is protected by a rupture membrane rated at 7 bars mounted on a double jointed flange and by a leak detection device.

In the top part of the condenser a chamber with removable cover is provided and pressurized with nitrogen to a pressure slightly above hydrostatic pressure containing the following elements :

- the pressurization pipe for this lock,
- the suction pipe and corresponding valve of the hydrogen loop vacuum chamber,
- the valve and pipe for injecting helium into the vacuum chamber,
- 4 stress gauge sensors to control the isolation vacuum (range 0-1 bar). Three of these provide the emergency shutdown function. They are isolated mechanically from one another, the fourth providing the alarm function,
- a Penning gauge to measure the isolation vacuum (range 10^{-2} to 10^{-3} torr).

3) Buffer tank

This is a Z2CN18-10 stainless steel cylinder tank of 600 cm diameter, 6 mm thick and internal volume approximately 470 litres located in the pool near to the condenser. It allows the hydrogen to expand during heating and thus maintains the hydrogen circuit pressure at under 5 bars with the source off.

In the top part there is a chamber pressurized with nitrogen (as for the condenser) with a removable cover and in which are located 5 stress gauge pressure sensors, 3 of which (range 0 - 7 bars) provide the emergency shutdown function and are mechanically isolated from one another.

III.2 Cryogenerator

This is common to both cold sources. It comprises

- 1) two vertical compressors with dry pistons and leak-tight labyrinths, with 2 cooling stages between each stage. These compressors are mounted in parallel.

- 2) The cold container holds the compact type helium-helium exchanger in aluminium. At the cold end of the exchanger on high pressure side, has been placed an active charcoal purifier essentially intended to protect the turbines against impurities. This cold container is located on the edge of the pool.

Adjacent to this cold container is a valve unit containing the helium circuit cold valves:

- 2 valves supplying the turbines,
- 6 valves controlling supply to either of the sources from one or other of the two turbines, or bypassing the condensers.

On each side of this valve unit there are the two housings containing the turbines with gas stages (rated rotation speed when cold : 180 000 rpm). The mechanical expansion energy is transmitted by the same shaft to helium turbocompressor-brakes. The heat given off by compression is evacuated by water circulation (0.6 m³/h).

- 3) Helium buffer and standby tanks, with a capacity of 6 m³:

- the buffer tank contains helium at a pressure slightly over the cycle low pressure. It serves as buffer to regulate the pressure of the cooling liquid.
- the standby buffer tank contains helium at a pressure of up to 25 bars. It is used to compensate installation losses during operation and ensure maintaining operation for 30 seconds in the event of electricity failure lasting more than 2 seconds.

- 4) The heater is an electric heat exchanger which heats the cold container to room temperature after shutdown of the turbines.

- 5) The cold purifier works on the principle of dessication and purification. This device is supplied with liquid nitrogen and has a regeneration circuit. A vacuum pump is used to drain the helium circuit.

III.3 Control equipment

This consists of

- remote controls for compressors and electrovalves,
- controls of turboexpanders with operating leds (decentralized in a rack on each turbine housing),
- the heating device control,

- pressure, vacuum, power and temperature measurements,
- display and processing of operation data,
- display and processing of faults in the different refrigerator parts.

III.4 Other equipment

- Conditioning equipments, valves, vacuum pumps, manometers, turbines, etc.
Conditioning operations are carried out from a programmable automaton,
- Also, a hydrogen discharge circuit. Hydrogen is discharged to outside the leak-tight chamber by a special circuit fitted with two electrically controlled pneumatic valves which confine the reactor. A nitrogen plug forming a lock is placed between two check valves in the housing of the hydrogen buffer tank.

IV. OPERATION OF THE ORPHEE COLD SOURCES

For each source there exists

- two normal operating conditions :
. refrigerated source,
. non refrigerated source.

IV.1 Refrigerated sources

Each cell is supplied with liquid hydrogen.

The refrigerator uses helium. This is compressed between 2 dry compressors in parallel and brought to room temperature by two water coolers. Then the high pressure helium (HP approx 15 bars) is cooled by the low pressure helium (LP approx 3 bars) circulating in counter flow in the cold container. It reaches a temperature of around 25°K and is expanded in the 2 turbines in parallel with gas stages at a pressure of around 3 bars (LP). Expansion produces a reduction in temperature down to approximately 16°K. The flow treated by each of the turbines is sent to the condenser of one of the cold sources. It is heated to approximately 20°K, thus evacuating the heat necessary for condensation of the hydrogen in each source. Then the two low pressure flows return to the exchanger. On leaving the exchanger, the LP whose temperature is around room temperature returns to the compressors suction line.

High pressure and low pressure are regulated automatically by means of channeling excess from HP into LP or supplying extra into HP from the backup tank.

Power is regulated on each loop by injection helium at room temperature, taken from the HP circuit, downstream of the turbines.

This operation is automatic.

IV.2 Non refrigerated sources

Before reactor start-up, the hydrogen circuit of the source or sources used was drained then filled with helium at a pressure around atmospheric pressure.

The vacuum chamber of parts in the pool is filled with helium at a pressure between 100 and 500 torr.

V. ORPHEE REACTOR COLD SOURCES : SAFETY ANALYSIS

Generally speaking, it can be said that the specific risks of this installation stem from the use of hydrogen, particularly liquid hydrogen in the reactor envelope and around the core.

The safety "philosophy" consisted of minimizing the quantity of hydrogen handled, locating it in a compact installation immersed in the pool, and taking maximum precautions in its handling and monitoring of the installation in order to have it and the reactor in the most inert condition possible in the event of an incident : shutdown of cooling and reactor shutdown, simultaneously or consecutively.

Only two parameters affect the reactor emergency shutdown sequence. These are

- the pressure of the hydrogen circuit, maximum value 3 bars,
- the pressure of the isolation vacuum, maximum threshold 0.9 bar.

V.1 Analysis of cryogenic risks

A check must be kept on

- 1) the quality of hydrogen used. The acceptable impurity level is limited to 50 ppm. This quality is controlled by double analysis (factory and acceptance) and before utilization by the user (chromatographer).

- 2) the temperature of the liquid hydrogen circulating in the cold loop, limiting to a low threshold the temperature at condenser input (15°K) and at turbine output (~ 14°K).
- 3) the pressure reigning in the vacuum chamber formed by the reactor thimble :
 - vacuum always better than 10^{-4} mbar,
 - reactor shut down automatically if the pressure in this chamber exceeds 0.9 bar,
 - a safety valve puts the vacuum chamber into communication with the outside if pressure reaches 7 bars.
- 4) maintaining the vacuum chamber in the event of fast hydrogen vaporization following a sudden rupture of the hydrogen cell. This chamber is designed to withstand an overpressure of 18 bars (static pressure).

The stainless steel hydrogen cell comes under scope of a plan to guarantee its quality of manufacture.

It can also be stated that this incident leads to a thermal shock of the wall of the vacuum chamber limited to some twenty or thirty degrees in some twenty or thirty seconds.

Similarly, rupture of the vacuum chamber following an accident external to the cold source would cause a sudden ingress of heavy water and sudden heating (and, therefore, vaporization) of the hydrogen. This pressure peak would not exceed a few bars (refer also to V. 3.2).

In addition, the circuit has been dimensioned so that load losses induced by the return tube to the vaporized hydrogen buffer tank are small.

- 5) that no leak appears between helium and hydrogen at the condenser. To ensure this, hydrogen pressure is limited to the safety threshold which provokes reactor emergency shutdown.

The exchanger tube bundle is also designed for a pressure of 18 bars.

V.2 Analysis of chemical risks

These risks stem from the use of hydrogen and its chemical reactivity with oxygen in the air.

- 1) The hydrogen circuit of each source is filled and drained with the reactor at shutdown and pool full. The total quantity of hydrogen contained in each source is limited. These operations are carried out according to a given procedure using an automaton.

The hydrogen discharge pipe is kept under nitrogen atmosphere. Successive nitrogen rinses are carried out during draining until the quantity of hydrogen remaining in the mix is less than 5%.

- 2) Reaction with hydrogen of the oxygen remaining in the hydrogen.

It was considered that oxygen present in trace form in the hydrogen could concentrate in solid state in the liquid phase and be carried wholly into the cell where it might react explosively with the hydrogen.

The maximum energy released by the explosion of the total quantity of oxygen thus introduced is under 100 Joules, a threshold usually considered as without effect on the mechanical structures.

- 3) Air-hydrogen reaction following air ingress into the chambers.

The highly improbable hypothesis was chosen according to which this risk followed an external attack of the source after uncovering of the hydrogen circuit, the initial condition before the reaction being a mix of oxygen and hydrogen in stoichiometric proportions. The effect of peak pressure on the wall of the vacuum chamber has been verified as less than the effect obtained by application of the same static pressure, this being designed to withstand 18 bars. The elongation value was checked and found to be around half of the elongation to the elastic limit, this would be reached at a peak pressure of around 80 bars, the static pressure to attain the same being 150 bars.

- 4) Hydrogen leak in the reactor hall.

This risk would follow an external aggression on the source.

The most probable scenario is a rapid dilution of the hydrogen beyond the inflammability limit. However, if dissipation was total and rapid and if a reaction occurred within this limit, a deflagration would occur within a space of 2 to 50 m³ above the pool. In stoichiometric proportions, the chemical energy would be about 25 megajoules which, in the 20,000 m³ of the hall, would result in an increase in pressure of around one millibar and a temperature rise of around 1°C.

Hydrogen is permanently monitored in the reactor hall.

V.3 Analysis of operation-related risks

1) Refrigerator shutdown

A sudden shutdown of cooling results in hydrogen vaporization within twenty to thirty seconds and its expansion in the buffer tank up to a pressure of 4.5 bars, whereas the cell temperature rises rapidly under the effect of gamma radiation.

Calculation arrives at a maximum temperature of 425°C in the absence of exchange gas in the vacuum chamber (thimble).

The reactor is automatically shut down by the hydrogen pressure maximum threshold and the isolation vacuum chamber is filled with helium. This action is automatic. One can then drain the hydrogen circuit, rinse it, fill the circuit with helium then return to normal reactor operation.

2) Heavy water leaks

The reactivity effect on the reactor is positive and limited to approximately 65 pcm. This risk is easily controllable by the operator.

3) Structures activation

In addition to conventional activation of the structures and conventional deterioration of the mechanical properties, one should look at the helium production generated by activation of the ⁵⁹Ni. This problem is dealt with under chapter VI.2.

VI. DESIGN OF THE ORPHEE REACTOR HYDROGEN CELLS; POST IRRADIATION EXAMINATION

VI.1 Design

When designing the ORPHEE reactor, it was decided not to renew the option taken for the cold source of the Grenoble high flux reactor. For ORPHEE, the reactor operation is independent of that of the cold sources. Therefore, it is able to maintain the reactor in operation with the sources not refrigerated.

To confine the hydrogen, we therefore chose an alloy suitable for use in severe environmental conditions particularly in regard to temperature, hydrogen and irradiation. This option rejected the use of aluminium alloys and necessarily looked towards the choice of high strength stainless steel or refractory type steel alloys.

Indeed, having chosen the shape of the cell, calculation of stresses in the material making up the envelope showed that for the extreme operating conditions envisaged; 425°C and a wall thickness of 0.8 mm, the zones under highest stress were working at 35 hb.

In the light of experience acquired in the domain of radiation applications, choice from the outset fell upon two alloys, Inconel 718 or the A286 alloy. However, the effects of irradiation led to envisaging limiting the boron concentration, to avoid any massive production of helium by n.α reaction on the boron 10.

In addition, in specialist opinion, the A286 (or ATVSMO) proved less sensitive to hydrogen, whilst showing less risks of helium formation due to radioactive relationships of the irradiated ⁵⁸Ni.

We have the following figures :

		INCONEL 718		A286 (ATVSMO)	
Ni%		55		26	
20°C	0.2%.hbar	108		64	
	R in hbar	132		98	
	A%	16		25	
at high tempera- ture	0.2%.hbar	105	at 650°C	98	at 400°C
	R in hbar	88		64	
	A%	16		25	

Therefore, the A286 was finally chosen although uncertainty remained as to the two essential points :

- the combined effects of irradiation and hydrogen on the chosen material,
- brittleness due to helium produced by (n.α) reaction on the nickel and boron.

The boron was limited to a low value : 10 ppm, from the outset.

VI.2 Results after irradiation

VI.2.1 Operating method

Natural nickel contains approximately 67.5% of ^{58}Ni .

Under irradiation, the reaction on the ^{58}Ni is written

The total cross-section of the ^{59}Ni is equal to 92 barns for thermal neutrons at 2200 m.s^{-1} .

The ^{59}Ni is considered stable (period 8.104 years), helium production results from the thermal irradiation of the ^{59}Ni produced according to the scheme:

The total cross-sections indicated above are taken from various references of WIFFEN and ALLEN (1), and ASGHAR (2).

An evaluation estimates the quantities of helium formed in the cell structures for an increasing rate of irradiation.

The thermal flux in the irradiation position is not isotropic. The face of the cell turned towards the core is more heavily charged than the face turned towards the channel (this

anisotropy does not exist for the SF₂ source). In addition, the flux depression generated by the cell in the heavy water reflector must be taken into account.

The first ORPHEE cold source was removed from the reactor in July 1987 and submitted at post-irradiation examination.

On each face of the irradiated hydrogen cell, 3 series of 5 samples for tensile testing were taken in order to determine the main mechanical characteristics of the irradiated material, carry out fractographic examinations to determine if the fractures are of ductile or fragile type (figure 5). In addition, some sample elements were used to assess the quantity of helium occluded in the basic material. The samples were cut by electroerosion; the method having been developed on a reference cell. Samples were also taken using the same operating method on a non irradiated cell to prepare a set of reference samples.

VI.2.2 Measuring the quantity of helium and hydrogen contained in the cold source hydrogen cell

The samples are placed in tungsten crucible and kept under vacuum by a primary pumping (vane pump) and secondary pumping (molecular pump) system.

Gas sampling is done through induction heating of samples, until melting if necessary. The extracted gases are collected using a mercury pump (Toepler pump).

Two methods are used to analyze the helium and hydrogen :

- either chromatography in gaseous phase,
- or mass spectrometry.

After each series of measurements, the installation is returned to atmospheric pressure to introduce the new samples. It must therefore be "de-gassed", i.e. be placed under the best possible vacuum for an extended pumping time with high temperature heating sequences (over 2000 °C) at set intervals in order to eliminate the residual gases of the installation.

Before and after each measurement, it is necessary to make a blank reference, i.e. a sample of the residual gases from the installation having operated for the same heating time with the same vacuum and temperature as the real measurement. For each gas assessed (here, helium and hydrogen), the blank reference volume is subtracted from the test volume.

Absence of helium in the blank references proves that all of this gas released during heating of the samples is recovered during pumping. Sources of error in measuring the helium mass concentration in this case occur during weighing of samples ($\pm 1\%$), measuring the volume of gases sampled by the mercury pump ($\pm 2\%$) and of the analysis method ($\pm 1\%$), i.e. in all $\pm 4\%$ of the value obtained.

The results concur fairly well with calculated estimates and, for the more irradiated face of the hydrogen cell, give a quantity of 907 ppm of atoms for 543 ppm of atoms for the less charged face. This result corresponds to an irradiation of 1000 days full power equivalent.

As regards hydrogen, the measurement method is much trickier due to the extensive but variable presence of hydrogen in the blank references, this can be explained by two main reasons :

- hydrogen tends to become trapped in the pipes much more than other gases, particularly helium,
- it is difficult for the installation used in 1987 to de-gass the pipes suitably after introducing samples into the system prior to assessment of the quantities obtained.

VI.2.3 Mechanical tests (figure 6)

Tensile tests were carried out. The test samples have a useful length of 12 mm; the fillet radius is 2 mm; and the width of the useful part is 3 mm. These test samples have a head 10 mm wide drilled with a 4.6 mm diameter hole for attaching the pin.

The tensile tests are carried out on an INSTRON static traction machine. Heating is done by an image oven; the temperature is controlled by means of a thermocouple placed against the sample. It is necessary to heat for 15 to 20 minutes to stabilize the dimensions of the attachment chain before the tensile test. If the temperature is stable at $\pm 1^\circ\text{C}$, temperature measurement is accurate to around $\pm 20^\circ\text{C}$.

The tensile tests are carried out at a constant traction speed; a 5,000 kg cell enables measuring the load. During a test, the evolution of the load over time is recorded for a known speed of movement.

The test curve highlights the following parameters :

- R_0 apparent limit of elasticity,
- $R_{p0.2}$ limit of elasticity at 0.2% plastic deformation,
- $R_{p0.5}$ limit of elasticity at 0.5% plastic deformation,
- R_M tensile strength,
- A_R distributed elongation,
- A_T total elongation.

Three temperature tests were selected :

- room temperature to find out hydrogen brittleness,
- 425°C to find out the characteristics of the liquid hydrogen cell functioning, without cooling and with the reactor at full power,
- 550° and 650°C to examine the cell strength limits (incident range).

Results are always compared to a reference sample heat treated for 16 hours at 725°C corresponding to the so-called aging treatment chosen for the steel used in the cell.

The tensile tests at temperature were sometimes preceded by 10 days' treatment at 425 - 550 or 650°C under vacuum.

Results show

- a very minor influence of the sample deformation speed,
- steel characteristics maintained at 425°C,
- considerable reduction of mechanical characteristics for 550° and 650°C.

VI.2.4 Fractographs (figure 7).

After traction, a few samples were examined under the electronic scanning microscope.

The fractographs highlight differences between two identical temperatures ranges for the reference material and for the irradiated material :

- at 25°C and at 425°C, rupture is cup-shaped ductile transgranular,
- at 650°C rupture is mixed, partly intergranular, partly cup-shaped ductile transgranular.

For the irradiated material and for the deformation speed of 8.10^{-5} s^{-1} , the proportion of intergranular rupture (shorts) is virtually the same as for the non irradiated reference.

VI.2.5 Conclusions on the post-irradiation tests

The mechanical behaviour of the irradiated material up to a test temperature of 425°C, considered the maximum limit of operating temperature in the reactor without cooling, is satisfactory for an occluded helium quantity of around 950 ppm of atoms.

The elastic limit at 0.2% of plastic deformation remains good after 10 days heat treatment at 425°C under primary vacuum and virtually identical to that found on the non irradiated reference material.

Also, ductility remains acceptable. These results are confirmed by the fractographic examination.

This is why the CEA decided to pursue irradiation of the second ORPHEE cold source.

This will be removed from the reactor during summer 1990. If our evaluations are correct, it will have reached approximately 1500 ppm of occluded helium atoms.

REFERENCES :

1. Wiffen and Allen, Farrar, Bloom, Gabriel, Kerr and Perez : The production rate of helium during irradiation of nickel in thermal spectrum fission reactors. AUGUST 1981, Journal of Nuclear Materials.
2. Asghar, Emsallen, Sjostrand : Thermal neutron induced charged particle reactions on ^{58}Ni , ^{59}Ni , ^{61}Ni . Z. Phys. A282 (1977) 375.

1. core
2. heavy water reflector
3. pool
4. primary coolant system
5. secondary system
6. heavy water system
7. control rod drives
8. heat exchanger
9. pump
10. pool drain tank
11. low-temperature source
12. high-temperature source
13. tangential channel
14. experimenters' area
15. neutron guide
16. reactor building

Figure 1.

Figure 2.

SOURCE FROIDE ORPHEE

Schéma de principe circuit hydrogène

Figure 3.

Courbe de gain

SOURCE FROIDE ORPHEE

Schéma de principe circuit hélium

Figure 4.

SOURCE FROIDE ORPHEE
Prélèvement d'éprouvettes de traction
sur la cellule irradiée

Figure 5.

SOURCE FROIDE ORPHEE

Evolution des propriétés de traction

1 = Face 1 la plus irradiée 2 = Face 2 la moins irradiée 0 = Témoin traité 16h à 725° C

Figure 6.

Cellule hydrogène ORPHEE après irradiation
Fractographies

Figure 7.

Cold Sources of the ORPHEE Reactor

Paul Breant

Questions/Answers/Comments

(P. Brewster)

Question:

How will standby cooling be provided to the Al chamber if the refrigerator is shut down?

Answer:

If the refrigerator is shut down, the reactor is automatically shut down too. The temperature limit of the aluminum cell, containing the liquid hydrogen, is 380K.

THE RISØ COLD NEUTRON SOURCE

Kurt Nørgaard Clausen, Jørgen Westermann and Kjeld Bue Olsen
Risø National Laboratory
DK-4000 Roskilde
Denmark

ABSTRACT

The Risø cold source was the first system with a supercritical hydrogen moderator (15 bar 38 K). The moderator chamber is made from an aluminium alloy AlMg3 (5052-0). Cooling is provided by a Philips-Stirling B 20 cryogenerator. The safety of the facility is ensured by the use of tripple containment preventing contact between hydrogen and air. The reactor operation is independent of the cold source. During 15 years of operation, cold neutrons have been available in more than 95% of the time.

I. INTRODUCTION

The DR3 reactor at Risø is a 10 MW heavy water moderated Pluto type reactor. The supercritical hydrogen type (15 bar 38 K) Risø cold source⁽¹⁾ is situated in one of the tangential beam tubes see Fig. 1, and has been in operation since 1975. The thermal and fast neutron flux at the cold source position is approximately 6.6×10^{13} n/cm² sec and 14.3×10^{11} n/cm² sec, respectively.

Fig. 1. Layout of beam tubes with CS (cold source), TS (thermal source) and neutron scattering instruments around the DR3 reactor. The cross hatched area is the reactor core.

The Risø cold source is operated independently of the reactor, and for the neutron beam users there are two important figures of merit, the availability of cold neutrons, and the gain factor. During 15 years of operation cold neutrons have been available for more than 95% of the time. The gain factor, defined as the monochromatic flux at the sample position with the cold source relative to the flux with the previous thermal source (water

Fig. 2. Cold flux gain factor

source at 350 K), has been measured at the TAS 1 position (see Fig. 1) and is shown in Fig. 2. A schematic diagramme of the Risø cold source with the supercritical hydrogen system is shown in Fig. 3.

II. THE SUPERCRITICAL HYDROGEN SYSTEM

Hydrogen at 15 bar abs. is above the critical pressure (≈ 13 bar abs.) and always in a single phase. The operating temperature can be varied between 28-40 K with corresponding hydrogen densities between 63 g/l and 12 g/l. (The density of liquid hydrogen at 1 bar and 20 K is ≈ 71 g/l). Operation without phase changes and tunability of the hydrogen density are advantageous aspects of the supercritical system. The Risø source operates in the temperature range 36-40 K.

Fig. 3. Principles of the supercritical cold neutron source

The hydrogen is cooled by cold He gas (see Fig. 3). The He gas is cooled to between 14 and 30 K by means of one of the two Philips-Stirling four cylinder, two-stage cryogenerators. The hydrogen circulation is forced by a fan (H-Fan in Fig. 3). The hydrogen pressure is kept constant by the hydrogen buffer and supply system, which is a 4 m³ vessel placed outside the reactor containment. This volume is sufficient to prevent the pressure falling below the critical pressure and thus prevents the formation of two phase hydrogen.

The buffer and supply system is disabled if the pressure falls below 14 bar abs. The high pressure safety is provided by relief valves (outside the reactor building) which are activated at 18.2 and 18.8 bar abs.

The cold neutron source can be started independently of the reactor. The cooling down time will be longer, if the cold neutron source is started, when the reactor is already operating (Heat load $\approx$ 400 W at a reactor power of 10 MW). The cold neutron source can be shut down independently of the reactor.

During stand-by cooling the hydrogen is circulated through an external loop with sufficient cooling capacity to keep the moderator chamber below 100°C.

III. SAFETY PRECAUTIONS

Hydrogen alone is completely harmless, and a hazard can only occur if oxygen is present too (mixture between 4% and 75% hydrogen in air). The hydrogen/oxygen hazard may occur in two ways.

Firstly, if some source of ignition (temperature $> 570^{\circ}\text{C}$, energy of ignition $> 20 \mu\text{J}$) is present, the elements combine exothermically to form water. Secondly, if oxygen from air is irradiated at cryogenic temperatures, ozone is formed and nitrogen may form oxides and ozonides of nitrogen, which decompose explosively and may initiate a hydrogen/ oxygen reaction.

The basic principle for safety of the cold neutron source is to preclude any possibility that air may enter either the hydrogen system or regions of the equipment containing hydrogen, especially at cryogenic temperatures and in fields of high radiation.

By adopting a triple containment philosophy the basic principle for safety is fulfilled. For the cold neutron source all hydrogen equipment inside the reactor is contained within a high-vacuum system (see Fig. 3), which is surrounded by a helium system at a small positive pressure, so that a leak in the helium blanket or the hydrogen system can be detected.

A special filling procedure for hydrogen into the high pressure system prevents air contamination. The purity of the hydrogen is checked by periodic analysis of gas samples from the system.

The safety instrumentation monitors temperature and pressure at all the key points in the system. According to the importance of any deviation from the normal operation, the safety instrumentation leads to 3 levels of action:

1. Shut down of reactor by activation of the scram system,
2. Shut down of the cold source
- or 3. Change the cold source into stand-by cooling.

To prevent unnecessary shut downs, these three levels of actions are activated from 2-out-of-3 systems.

IV. THE COLD MODERATOR CHAMBER

The cold moderator chamber (see Fig. 3) is of superelliptic axisymmetric shape. It is fabricated from an aluminium alloy AlMg3 (5052-0). The two halves of the chamber is pressed from a plate and welded together. The large outer diameter is 138.5 mm, the small outer dimension is 70 mm and the wall thickness is 5.5 mm. The hydrogen pipes are connected to the chamber through nozzles placed in initially low stress areas. The design conditions were 20 bar absolute, 100°C, and a stress intensity of 46.7 N/mm² (= 2/3 R_{0.2}^{100°}). The stress analysis was performed in two steps. 1: Axisymmetric analysis of the moderator chamber (without nozzles) using the general finite element program ADINA⁽²⁾, and 2: 3-D finite element analysis of the local influence from the nozzles. The material properties are given in German Industry Standards⁽³⁾.

On irradiation AlMg3 is converted to a precipitation hardened alloy⁽⁴⁾. The precipitates are derived from insoluble transmutation produced silicon and include Mg₂Si. The flow stress and tensile strength are increased but the ductility is decreased. From the investigation of a high pressure rig used in the core of the DR3 reactor which has received a total dose of 2.5×10^{22} n/cm² (2×10^{22} n/cm² thermal and 0.5×10^{22} n/cm² fast neutrons) an acceptable total fluence of 4.5×10^{22} n/cm² has been estimated for our moderator chamber, i.e. sufficient ductility should remain until the unit has been operated for 25 years.

V. PERFORMANCE - RUNNING EXPERIENCE

Since 1975 Risø has had a very reliable source of cold neutrons, which has been essential for a large number of successful neutron scattering experiments within solid state physics (SANS, magnetism, phase transitions, fast ion conductors, nuclear magnetism) and materials science (texture, internal stress, crystallization kinetics). The cold source serves 5 out of 7 neutron spectrometers at Risø (see Fig. 1). The availability of cold neutrons is over 95%. Stand still of the cold neutron facility has essentially always been due to vacuum leaks or cryogenerator problems. With our refrigeration system it has proven essential to have two cryogenerators in order to have sufficient time for general maintenance and to ensure as short a disruption in the supply of cold neutrons as possible.

VI. ACKNOWLEDGEMENTS

B. Bukholt, O. Gunneskov, K. Hansen, K. Jensen, N.C. Jessen, B. Lebech, J.A. Leth, J. Qvist and P.R. Winstrøm are greatly acknowledged for discussions and for providing internal notes and reports.

VII. REFERENCES

1. K. Jensen and J.A. Leth, "The Cold Neutron Source in DR3", Risø Report, Risø-M-2246 (1980), 1-30.
2. K.J. Bathe, "ADINA: A finite element programme for automatic dynamic incremental nonlinear analysis", MIT Report 82448-1, Sept. 1975.
3. AD-Merkblatt W6/1: Werkstoffe für Druckbehälter. Aluminium und Aluminiumlegierungen, Knetwerkstoffe.
4. K. Farrel, "Microstructure and tensile properties of heavily irradiated 5052-0 aluminium alloy", Journal of Nuclear Materials 97 (1981), 33-43.

The GKSS Cold Neutron Source

W. Krull

GKSS-Forschungszentrum Geesthacht GmbH
Geesthacht, West Germany

I. THE FRG RESEARCH REACTORS

The GKSS research centre Geesthacht GmbH is operating the research reactors FRG-1 and FRG-2 with power levels of 5 MW and 15 MW. The reactors became critical in 1958 and 1963. The reactors are fueled with MTR type fuel elements and are in operation ca. 180 d/a to 250 d/a. Both reactors are located in a connecting pool system (fig. 1) and operated by the same staff. The FRG-2 is used for testing power reactor materials like pressure vessel steels, fuel rods, etc. The FRG-1 is equipped with beam tubes and used for different fundamental and applied research programs and for NAA, isotope production and neutron radiography.

II. PRE-PROJECT PHASE

At the beginning of the eighties, it could be seen that there was a decreasing need for performing tests in research reactors for power reactor safety or future development of power reactor materials like we are doing in the research reactor FRG-2. Therefore, the decision was made to start considerations about a renewal of the experimental situation of the second reactor, the FRG-1. At the same time, the decision was made to go ahead with a materials research program at GKSS. This was an excellent starting situation for the considerations. Within the first plans, the installation of a cold neutron source got high priority. But it was clear at that time: if there will be the decision to install a cold neutron source, we don't want to do the design work by ourselves; we want to buy the source from competent

suppliers. We don't want to make research on cold neutron sources, but we want to do research work with cold neutrons.

First of all, a comparison of the fundamental safety aspects of both types of a cns (liquid or gaseous H_2^*) was made and discussed with the licensing authorities and their consultants. We got a principal statement that both types will be made licensable in Germany. This was the starting point for detailed technical and economical discussions with the two suppliers of cold neutron sources: Technicatom (liquid H_2) and the consortium Interatom/RisØ (gaseous H_2). It had been clear during all these discussions with both vendors that changes in the design, construction, inspection, documentation, etc. would be necessary due to the demands coming up from a licensing procedure in Germany. Before signing the contract, a very detailed comparison about the different designs, technical backgrounds, economical aspects, etc. had been made. Within this comparison, it could be shown that from the output of cold neutrons (gain), both designs should be nearly identical as the hydrogen density of liquid H_2 at 1 bar and 20 K is more or less the same as for gaseous H_2 at 15 bar and 25 K (fig. 2). This is in good agreement with published gain factors. After long and detailed discussions with both competent suppliers, a contract with the consortium Interatom/RisØ was signed in June 1984 to deliver a complete and full functioning cold neutron source. To reach this goal in time, large efforts of the GKSS research center in all phases of the project have been necessary, too.

III. MAIN DESIGN FEATURES OF THE GKSS COLD NEUTRON SOURCE^[1,2]

The design features can be grouped into

- main physical and technical design features;
- additional technical design features; and
- demands on design from the licensing procedure.

The main physical and technical design features have been the following:

- moderator of cns (the diameter of the reactor pool is small)	H_2
- physical state of H_2	gaseous
- temperature of H_2	25 K
(> 14 K to avoid solidification of H_2)	

* D_2 has not been considered due to the limited geometrical conditions.

- pressure of H ₂ (> 13 bar to avoid liquidification of H ₂)	13, 9-17, 3 bar
- density of H ₂ (16 bar)	0,07 g/cm ³
- thickness of cns	4,2 cm
- diameter of cns	15,5 cm
- source material (low absorption cross section)	AlMg _{2,7}
- nuclear heating + heat losses	1,0 - 1,5 kW
- realized (guaranteed) gain	≥ 11 ($\lambda = 5 \text{ \AA}$)
- reflector material (no separated reflector coolant circuit, no space problems)	Be
- distance reactor - cns (optimal condition)	≤ 71 mm
- reflector between reactor and cns (slightly increased gain, easier)	H ₂ O
- gap between cns and reflector (optimal condition)	5,5 mm

Additional technical design features:

- the cns should be operated automatically, but manual operation should be possible;
- mechanical and electrical components shall be redundant where it is for technical and safety reasons necessary and economically justified, e.g., cold and warm hydrogen fans, freon standby coolers, H₂O cooling systems for cold fans, vacuum pumps, safety related instrumentation (pressure and temperature), compressed air supply, emergency power supply;
- health physics instrumentation should be installed; and
- low operating cost, especially no need for having shift personnel.

It was clear when signing the contract that demands coming up from the German licensing procedure must be considered from the beginning of the design

- the cns should not cause any accident which may affect the research reactor;
- the cns has to pass a licensing procedure;

- relevant rules and standards have to be looked at (in-pile and out-of-pile materials in the H₂ system, reliability of components);
- quality assurance, quality control and documentation [e.g., all welds in H₂ and in-pile system (H₂, vacuum and He) have to be inspected by independent consultants to 100 %];
- the probability for accidents with extreme low probability but severe damage potential has to be reduced (e.g., the wall thickness of the 20 bar H₂ and He buffers had to be increased to 20 mm);
- hydrogen leakages in buildings have to be avoided with passive technical means in the reactor building and H₂ monitoring where believed to be necessary;
- H₂ leakage monitoring in two small auxiliary buildings where the relevant rules for installations in explosive areas have to be used; and
- physical protection.

IV. A BRIEF DESCRIPTION OF THE CNS

The principal design of the cns can be seen in Fig. 3, which shows the following systems:

- a cold (25 K, 15 bar) H₂ system cooled down by a He refrigeration plant;
- a warm (-35°C, 15 bar) H₂ standby system cooled down by freon coolers (1 out of 2)(this system is needed in case the reactor is in operation but the He refrigeration plant is not in operation); and
- a hydrogen pressure supply system (6,3 m³ H₂ at 13,9 bar to 17,3 bar).

To have the cold neutron source operating, the following systems are necessary:

- H₂ cooling circuit. The components of this system are the in-pile part with the moderator chamber (fig. 4) and H₂-piping, fans (1 out of 2) for cold H₂, H₂/He-heat exchanger, valves, temperature and pressure measuring channels;
- conventional He cooling plant;
- H₂ supply system, including H₂ buffer, valves, instrumentation, etc.;
- H₂ standby cooling system: fans (2 out of 3) for warm H₂, freon coolers (1 out of 2), valves, instrumentation, etc.;
- auxiliary systems: connecting liners, vacuum system, cold fan cooling system, H₂-relief safety box filled with He, compressed air system;
- instrumentation and safety system; and
- electrical power supply (standard and emergency).

V. MAIN SAFETY RELATED ASPECTS*

The design basis accidents for a gaseous cold neutron source are

- Instantaneous rupture of H₂- or He-buffer.
Protective action: selection of steel (1.4541) and increased wall thickness (1 mm per 1 bar which corresponds to power reactor rules). H₂ corrosion resistance has to be considered for the selection of steel and Al;
- Hydrogen/oxygen explosions.
Protective action: triple containment philosophy in building (fig. 5). Triple containment means hydrogen, Al (containment no. 1), vacuum, Al (containment no. 2), He, and Al (containment no. 3). Therefore, the hydrogen tubes are in vacuum which is in He. The He pressure is higher than the pressure of the surrounding medium (water or air). The pressure in the hydrogen, vacuum and He is being surveilled and combined with alarms, shutdown of the cooling plant and the reactor and etc. Therefore, inside buildings, no H₂/O₂-mixture can occur. Measures have been taken to avoid mechanical damage of this system.;
- Loss of cryogenic power (no standby cooling and no shutdown of the reactor is assumed).
The cns will melt between 10' and 20' as the heat produced in the Al-canning cannot be removed. It can easily be shown that the melting will stop after having a direct contact between the molten Al and the beam tube (which is identical with the 3. containment).
- Rupture of cns (moderator chamber). The pressure increases up to 12 bars.
Protective action: the vacuum chamber withstands this pressure. The He (3. containment) chamber is designed for 30 bar; and
- Freezing of H₂ in the H₂/He heat exchanger and connecting piping (no stop of the cryogenic plant is assumed). Protective action: A few cm of unisolated piping near the heat exchanger to remove heat through radiation to avoid blockage of the standby cooling loop and thereby a pressure increase in the moderator chamber.

The design of a cns can be made that way; all instrumentation may fail but nothing happens to the research reactor or third persons. Therefore, a cns has to be treated as a complex and expensive experiment. To pay between 6 and 10 million US \$ for the safe operation of one litre of H₂ under low temperature conditions near to a research reactor core is only possible for comparably rich countries.

* for more details see table 1.

VI. TIME SCHEDULE AND LICENSING PROCEDURE

In the following, the steps realizing the cns project are being described

a.	Pre-project phase	06.83*
b.	Contract with the consortium Interatom/RisØ	06.84
c.	License application	06.84
	After explaining the cns project to the licensing authorities in the pre-project phase, it has been clear from the beginning that for the on-site construction and operation of the cns an amendment to the existing operation license of the research reactor was absolutely necessary. During this license procedure, the licensing authority asks relevant organizations for consultants' reports for the design and safety aspects of the cns, fire protection demands on the cns and the reactor building, working restrictions in explosive areas, etc.	
d.	Internal safety committee	02.85
	Positive votum for design and construction	
e.	Report of the consultants of the licensing authority	11.85
	This report was taken, too, for the HMI cns some months later	
f.	License for construction and operation of the cns	07.86
	Before getting the license, the consultants' report had been discussed in detail and it was decided that for getting the license no public hearing was necessary. The reason for this decision was as follows: from the operation of the cns, no addition to the overall operational risk of the FRG-1 could be seen. The license contains a larger number of conditions to	
	- technical design, e.g., around 100 technical reports have been written before and analysed to confirm the safe design;- inspections during fabrication, construction and putting into operation;- fire protection;	

* 06.83 = June 1983

- quality assurance, e.g. the technical design reports, specs, etc. have been checked page by page by the consultants, and a separate fire resistant storage for all these documents was seen to be necessary; and
- written manuals for the different steps of putting into operation.

After having the license we were able to start the construction of buildings, etc., on site. All non-GKSS specific conditions and reports have been taken for the HMI source, too.

g.	Buildings ready	12.86
h.	On-site construction of the cns starts
The original contract had foreseen construction at RisØ and later on transportation of the cns to GKSS and an adjustment to GKSS conditions. This was believed to be not practicable and not realizable in due time.	01.87
i.	FRG-1 shutdown
After some repair within the FRG-1 pool, all in-pile components were installed and cold tested.	04.87
j.	FRG-1 critical	03.88
k.	Cns cold operation over 3 weeks with no reactor power
After this cold test, some additional inspections and procedures had to be made. Many troubles with warm and cold H ₂ and He leaks had to be solved. This took us several months. Difficulties with an in-pile part of the reactor and the construction of experiments stopped the putting into full operation procedure of the cns and the reactor for some months, also.	04.88
l.	Permission of the licensing authority for full power operation of cns and reactor.	04.88
m.	FRG-1 and cns on full power (5 MW and 25 K)
After this date, the operation of the cns stops for an additional 3 months due to leaking cryovalves at cold temperatures.	06.89

Within the final measurements, some of the important characteristics have been measured, such as

- 8 h* for the cooling down time with reactor on full power;
- After stopping the cryoplant, the warming up takes 4 h before the standby cooling starts (1 cold fan is running during that time);
- The cold He and the cold H₂-temperature control behaviour during a short shutdown of the reactor has been determined. This behaviour is excellent (fig. 6); and
- The gain of cold neutrons has been determined. A gain of 13,8 for 5 Å neutrons has been measured (fig. 7). This is in good agreement with calculations.

VII. ADDITIONAL EFFORTS IN UPGRADING THE NEUTRON FLUX

In addition to the construction of the cold neutron source, GKSS has undertaken more efforts to a further increase of the neutron flux for beam tube users, such as

- reduction of the FRG-1 core size by a factor of two**	~ 1,5
- installation of a Be metal block reflector (32 CM thick)	1,45
- 5 mm water gap around the beam tubes	1,15
- renewal of beam shutter	1,20
- increasing the full power days/s from 800 MWd/a to 1200 MWd/a	1,5

Therefore, there is an additional increase of a factor of 4,5 in cold neutrons, so that there is an overall increase of

5 Å neutrons by a factor of	> 60
10 Å neutrons by a factor of	> 110.

VIII. EXPERIMENTS WITH COLD NEUTRONS

During the design, construction, and putting into operation time of the cns, a total renewal of the experimental facilities in our experimental hall had been discussed, decided, constructed and started operation. A general overlook can be taken from fig. 8^[4], especially the SANS activities are used for

* coming from demands on max temperature differences in the H₂/He heat exchanger and the leaking cryovalves.

** see [3]

- precipitation structure in iron-copper and pressure vessel steels as a function of irradiation (fluence);
- determination of hydrogen distribution in welded alloys used for underwater techniques;
- structural defects in amorphous alloys;
- structure of polymers; and
- development of so called supermirrors.

For more information, see [4].

IX. REFERENCES

- [1] W. Krull, K. Hansen, J. Stein, "The Cold Neutron Source for the FRG-1 Research Reactor at the GKSS Research Centre", IAEA-SR-119/27, Copenhagen 1985.
- [2] W. Krull, "Die Kalte Neutronenquelle am Forschungsreaktor FRG-1", Atomwirtschaft XXIII (1988), 43-47.
- [3] W. Krull, "Enrichment Reduction Activities for the FRG-1 and FRG-2 Research Reactors", RERTR International Meeting, San Diego 1988.
- [4] R. Kampmann, "Novel neutron guides and new instrumentation for materials research at the FRG-1 research reactor in Geesthacht", IAEA-SM-300-012, Grenoble 1987.

TABLE 1: Design-based accidents for the CNS

Assumed causes of accident	measures/barriers		Effects of accident
Accident: Breakage of the moderator chamber			
Postulate	passive:	Active rupture disk - 100 (VacI/VacII) - 101 (VacII/relief chamber) Open parallel safety valves He-III-Ve 261/262 Throttle the H ₂ being subsequently fed from the buffer tank by reducing the cross section at shutoff valves H-Ve 26/27	Pressure rise in vacuum chamber to a max. of 12 bar. The vacuum chamber remains intact as a pressure-surrounding enclosure. A further barrier is available in the form of the beam tube (design 30 bar). Release of hydrogen via safety valves He-III-Ve 261/262 and the release chimney into the open air. Moderator chamber and vacuum chamber must be replaced.
	active:	Closure of valves H-Ve 26/27*	
Accident: Total failure of the cooling system for the moderator chamber			
<ul style="list-style-type: none">- Failure of the hydrogen circulation system (stop of stand-by cooling, too)**- No flooding of vacuum I with helium- No reactor shutdown- No helium fed to moderator chamber	passive:	Vacuum chamber/beam tube Open check valves H-Ve 21/22	Melting of the moderator chamber after 10-20 min. The melt is collected by the vacuum chamber/beam tube, where it begins to solidify Moderator chamber and vacuum chamber must be replaced. No pressure build-up takes place during heating up of the moderator chamber, as hydrogen flows off through the check valves into the hydrogen buffer tank.

* To limit the loss of hydrogen

** Fan and electrical power supply are produced in redundant design

Assumed causes of accident	measures/barriers		Effects of accident
Accident: Breakage of the CNS beam tube, with destruction of the vacuum chamber and the H ₂ line in the CNS beam tube			
Boundary conditions* - FRG-1 not in position - CNS operated in warm condition and pressure relieved - Hydrogen buffer tank separated from hydrogen system Postulate: Dropping of heavy load a) System condition: Evacuation of H ₂ system b) System condition: No evacuation of H ₂ system	active: passive:	Long-term ending of pool water loss, e.g., interruption of evacuation Flow resistance of H ₂ line	Max. pool water loss of 42 l/min. Release of max. 10 g (approx 0,1 Nm ³ of hydrogen into the reactor hall, H ₂ /air remains below ignition limit.
Accident: H ₂ explosion inside triple enclosure			
Hypothesis	passive:	Triple enclosure of hydrogen	None, as the triple enclosure prevents the formation of potentially explosive H ₂ /air mixtures. The system is nevertheless designed to cope with the excess pressure.

Accident: Freezing of H ₂ /He heat exchanger			
<ul style="list-style-type: none"> - Reactor is shut down - Refrigeration system is not regulated - Refrigeration system is not shut down when helium temperature is too low - Refrigeration system is not shut down when hydrogen temperature is too low 	passive:	One section on each of the connection lines on the heat exchanger is not insulated, thus the connection to the stand-by cooling system cannot freeze.	Leakage of the H ₂ /He heat exchanger possible
Accident: H ₂ leakage in external area			
Postulate	passive:	Compliance with Explosion Protection Guidelines and TRB 600/610	Loss of H ₂ . No explosive mixtures will occur.
Accident: Rupture of H ₂ or He buffer tank			
Hypothesis	passive:	<p>Design and manufacture of the tank in accordance with the General Specification for Basic Safety.</p> <p>Selection of material which does not become brittle when subjected to H₂.</p>	None, as rupturing is prevented by the measures taken (Basic Safety).

Fig. 1

Fig.-2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

NEUTRON SCATTERING FACILITIES FOR MATERIALS RESEARCH

- SANS:** SMALL ANGLE NEUTRON SCATTERING FACILITY
- SANS 1: study of organic macromolecules using the interaction of polarized neutrons with polarized targets
 - SANS 2: study of precipitates, clusters, voids and bubbles in crystalline and amorphous solids with unpolarized or polarized neutrons
- DCD:** DOUBLE CRYSTAL DIFFRACTOMETER
- study of large creep, fatigue and sintering cavities in ceramics and high temperature alloys
 - study of decomposition of polymers
- DENS:** DIFFUSE ELASTIC NEUTRON SPECTROMETER
- DENS 1: study of short range order and clustering
 - DENS 2: study of hydrogen content in waste and heat affected zones
- FSS:** FOURIER STRAIN SPECTROMETER
- study of internal stresses in materials
- TEX-2:** FOUR-CIRCLE NEUTRON TEXTURE DIFFRACTOMETER
- study of textures in metals, alloys and polymers in various states

USE OF NEUTRONS FOR ENVIRONMENTAL RESEARCH PURPOSES

- NAA:** NEUTRON ACTIVATION ANALYSIS
- detection of trace elements in samples for environmental research
 - chemical analysis of alloys
- PNCG:** PROMPT NEUTRON CAPTURE GAMMA-RAY SPECTROMETER
- detection of trace elements in samples for environmental research
- GENRA-1:** JEESTHACHT NEUTRON RADIOGRAPHY FACILITIES
- non destructive analysis of materials

Fig. 8

Experimental

NEUTRON GUIDES

Neutron Guide	I	d/mm	d_{eff}/mm	λ_{min}	R/m	L/m	λ^*/m	coating
NG-1	3	9.0	30	90	1040	13	0.20	
NG-2-u	2	14.1	30	40	900	13	0.26	
NG-2-1	3	9.0	30	40	730	14	0.45	
NG-3	4	9.1	42	100	4400	24	0.10	
NG-4	15	100	3000	19	0.18			

(I: number of channels in laminar section; d : channel width; d_{eff} : total beam width; λ_{min} : beam height; R: curvature radius; L: length of curved section; λ^* : characteristic wavelength; SAM: supermirrors coating on top and bottom; Neut: Neutron)

The Berlin Cold Neutron Source

A. Axmann , C.O. Fischer

Hahn-Meitner-Institut GmbH
PO. Box 390128, D-1000 Berlin 39, FRG

0. ABSTRACT

The Berlin CNS has been installed to be operated in the 10 MW reactor BER-II with a cooling power of 2000 W at 25 K. The basic design-, engineering- and safety criteria are described.

1. INTRODUCTION

The Hahn-Meitner-Institut (HMI) operates research reactors since July 1958. The 50 kW Water-Boiler-Reactor BER-I was in service mainly for isotope production, activation analysis and the study of radiation effects until 1971. The 5 MW Swimming-Pool Reactor BER-II became critical in 1973 and was increasingly used for beam-tube experiments until 1985, when an upgrading program was started to meet the increasing demands of the users for higher neutron intensities and more advanced experimental facilities.

Increase of power level from 5 to 10 MW, reduction of core size and a fixed Beryllium- reflector with optimal fitting of the beam-tube noses to the reflector flux peak will improve the beam intensity up to a factor 10.

In addition a cold neutron source (CNS) with a bundle of neutron guides was installed instead of the thermal column in order to supply a great number of experiments in a new guide hall.

In these days the final tests of this 130 Mio DM project will be finished and we expect the license for operation in May of this year. This date was recently announced by the Lord Mayor of Berlin to the German Minister for Research and Technology.

2. BASIC DESIGN and LICENSING

After the principal decision of the Board of the HMI for the upgrading of the BER-II plant, the first edition of the safety report for the 10 MW BER-II with CNS, written by the HMI, was handed over to the licensing authority on Nov. 12, 1979.

Fig.1 The 10 MW BER-II

Detailed discussion with the licensing authority resulted, that a safety report for a research reactor has to follow the published guidelines for safety reports for German PWR power plants. So we asked the specialists from INTERATOM to fit our safety report to the German requirements of the atomic law and more than 20 different regulations, guidelines, technical codes and -rules and also to the actual decisions of the German High Courts.

The 3. edition of the Safety Report Reactor /1/ was completed in Aug. 1982, and displayed a conical beam tube, designed to withstand a pressure of 30 bar, for the installation of a CNS (Fig.1)

Detailed investigations were made until 1982 which showed, that a liquid CNS (system Grenoble/ Saclay with liquid hydrogen boiling at 20.4 K and 1 bar) from TECHNICATOME /2/ as well as a supercritical CNS (system RISØ with gaseous hydrogen at > 13.2 bar and 25 K) from the CONSORTIUM INTERATOM/RISØ /3/ can be operated safe within the conical beam tube of the 10 MW BER-II.

Fig. 2

Fig. 2 shows the different thermodynamical properties of the two types of CNS. A comparative study /4/ of the two versions under the aspects of neutron physics, technology, safety, licensing, maintainance, interfaces to reactor and experiments, and economy lead to the decision for the supercritical CNS by INTERATOM/RISØ.

A supercritical CNS is operated with hydrogen beyond the critical point ($p > 13.2$ bar, $T > 14.2$ K). The HMI-CNS is designed for a moderator temperature of 25 K. The pressure range is between

Fig. 3 Supercritical CNS, hydrogen circuits

13.9 bar (cold) and 17.3 bar (warm). The gaseous hydrogen is circulated by a blower with 1.1 l/s through moderator chamber and the H₂/He heat exchanger. If the main cooling plant (2000 W at 25 K) is shut down, a stand-by cooling system for -35 K keeps the moderator chamber at low temperatures if reactor operation continues (Fig.3)

After the public hearing about the Safety Report Reactor /1/ in Oct. 1983 with many of the 201 opponents, the budget for the project was given by the Minister for Science and Technology. The Letter of Intend to the consortium INTERATOM/RISØ for the CNS was signed on Nov. 21,1983 (contract June 28,1985) and the contract for the 10 MW upgrading of the reactor with INTERATOM on Dec. 15,1983.

It became apparent during the public hearing, that in view of the German regulations a CNS probably cannot be licensed as an experiment, but as a main part of the reactor. This would require the presentation of a Safety Report CNS to the public and a public hearing before the installation of the CNS can be licensed. In Dec. 1984 the HMI asked the licensing authority to handle the CNS in a separate procedure and presented the first edition of the safety report for the CNS.

Moderator chamber		H2- system	
AlMg3, flux th	5E13 /cm2 s	AlMg3, stainless steel	
max i. diameter	H2 155 mm	pressure	13.9 - 17.3 bar
max i. thickness	H2 60 mm	buffer vessel	8300 g H2
mean thickness	H2 42 mm	cold circuit	970 g H2
wall thickness	5.8 mm	piping	40 g H2
temperature	25-35 K	buffer vessel	20 bar, 6.3 m3
Cooling plant (He)		Stand by cooling (frigen)	
electr. power	200 kW	stand-by power suppl.	2 x 100 %
cooling power	25 K 2000 W	heat exchangers	2
He buffer	20 at, 6.3 m3	blowers	5
Cryogenic vacuum (Va I, II, I)		Helium (He I, II, III)	
pressure warm	1 E -6 mbar	pressure	1.3 bar
pressure cold	2 E -8 mbar		

Tab.1 Main data of HMI-CNS

The first construction permission with exclusion of the CNS was issued in Aug. 1985. Opponents sued at law against the construction permission. With decision from Dec. 22, 1986, the Berlin High Court allowed to continue the reactor construction with exception of the shielding plug in the thermal column and the conical beam-tube. These parts are of importance for the reactor as well as for the CNS : They have to fulfill the requirements as the first barrier against loss of water from the reactor pool and as the third barrier for the enclosure of the hydrogen of the CNS.

	Reactor	CNS
first safety report	11/79	11/84
final safety report	8/82	3/87
opponents	201	620
public hearing	10/83	6/87
contract INTERATOM/-RISÖ	12/83	6/85
expertise (TUV)	5/85	9/87
licence	8/85 TG 1 10/87 TG 1a	10/88 TG 2
Berlin High Court	12/86 (3/87) partial stop of construction 6/88 (1/89) stop canceled	
1. criticality	scheduled 9/87 real 5/90 ?	

Tab. 2 Schedule of licensing

The 5. edition of the Safety Report CNS /5/ was discussed in a public hearing on June 21-26, 1987 with several of the 620 opponents against the CNS. The 1. addendum to the 1. construction permission was issued on Oct. 29, 1987. On June 16, 1988 the Berlin High Court revised his decision from Dec. 22, 1986 so that the construction of the shielding plug and the conical beamtube was started. The installation of the components of the CNS itself was started after the reception of the 2. construction permission on Oct. 26, 1988. Also against this license the plaintiffs sued at law. The legal procedures against all licenses are continuing.

3. SAFETY CRITERIA

It was demanded, that the CNS has no impact on the safety of the reactor, even if all active systems for the control and regulation of the CNS fail. The main criteria are:

1. Exclusion of explosive H₂/O₂ mixtures
2. Integrity of the 2 barriers against loss of poolwater

These requirements are fulfilled by means of the following precautions:

1. For the cryogenic part of the hydrogen system and the warm parts within the reactor buildings a triple containment of the hydrogen has been constructed: 1. walls of the hydrogen system, 2. walls of the cryogenic vacuum, 3. walls of the enclosing Helium system.
2. The hydrogen system outside the reactor buildings, valve container, stand-by cooling box, H₂ buffer vessel, and filling station are performed in accordance with the rules for handling of pressurised and explosive gases. To avoid an instantaneous rupture of the big buffer vessels for H₂ and He (6.3 m³, 20 bar), these components were constructed under consideration of the strongest German rules for the pressure vessels of PWR and BWR power plants.
3. The rupture of the moderator chamber cannot destroy the surrounding vacuum chamber (30 l, 12 bar) within the conical beamtube (300 l, 30 bar).
4. Malfunction of the cooling systems.
 - a. if all protective systems of the CNS fail, the moderator chamber will melt within 6 min if reactor operation continues and within 45 min if the reactor is scrammed. The molten metal will be solidified at the cooled walls of the moderator chamber or of the conical beam tube.
 - b. if the cooling plant is not stopped when the reactor is scrammed, the H₂ will begin to freeze first within the H₂/He heat exchanger and stop the hydrogen circulation. An unisolated part of the hydrogen piping avoids the blocking of

the expansion lines to the stand-by cooling and the buffer vessels.

5. The triple liner is physically protected and the cranes above the CNS installation are blocked when the hydrogen is under full pressure. The handling of heavy loads and maintenance work at the hydrogen system and the triple containment requires special precautions.

4. ENGINEERING

The engineering of the CNS was performed by the consortium INTER-ATOM/RISØ under consideration of the safety report /5/. Among all the detailed studies of the constructors, a great number of reports had to be added to the safety report: On request of the experts and consultants of the licensing authority in total 46 so called "Ergänzende Unterlagen zum Sicherheitsbericht", and on request of the licensing authority herself in total 12 so called "Unterlagen zur Minimierung des Restrisikos". All these papers are part of the license and regulate in detail the procedures with respect to quality-control and documentation during design, fabrication, installation, operation and maintenance of the CNS.

The inpile parts of the HMI-CNS are shown in fig. 4. The conical beamtube is fitted to the shielding plug which now replaces the former thermal column. Two plugs are inserted: 1. a cryogenic-plug with the inpile-part of the CNS and a hole for a neutron guide and 2. the guide-plug with 4 neutron guides.

Fig. 4 HMI-CNS, inpile

The moderator chamber is designed according to AD- rules for 20 bar and 100 C. The wall thickness is 5.8 mm, the lengths of the inside axes 155 mm and 60 mm.

The vacuum chamber is cooled by heat transfer through the He gap to the poolwater and by an additional water cooling.

In a distance of ca. 140 cm from the moderator chamber, the neutrons leave the protective He I system and pass the first neutron window to enter into the neutron guide systems. Downstream in direction to the neutron guide hall, the neutrons fly in helium atmosphere through a rotary shutter to second neutron window. Then they pass a fast valve shutter at the entrance of the evacuated part of the guide system.

Fig. 5 HMI-CNS, 3 barriers, jointbox

The hydrogen is transported by the 3-barrier-transferliner from the inpile part to the jointbox (Fig 5). There the two main hydrogen blowers, the H2/He heat exchanger and cryogenic valves are arranged within a vacuum chamber surrounded by a helium jacket. The jointbox is connected by the 3-barrier-supplyliner with the components outside the neutron guide hall (2x 100 % stand-by cooling, H2 buffer vessel and H2 supply system)

5. OPERATION and CONTROL

The CNS operation is automatically controlled. The presence of the operator in the control room of the CNS is necessary only for supervision of the cooling down phase.

The CNS instrumentation indicates ca. 150 different alarm signals on the main panel in the control room of the CNS in comparison to ca. 450 different alarm signals in the control room of the reactor. If any CNS alarm occurs, a special alarm line to the main control room of the reactor is activated.

The CNS is equipped with redundant components and 2 of 3 instrumentation for the operation and control of the hydrogen-, the vacuum- and the helium-systems.

The following automatic actions will prevent the components of the CNS from severe damage (Tab.3):

1. Temperatures H2- system

< 17 K		stop cooling plant
> 100 K		change H2 blower
> -35 C		start stand-by cooling
> 95 C	RESA	separation buffer vessel
		reduction H2 pressure to 1.5 bar
		backfilling vacuum I with helium II
> 200 C		bleeding H2 system with He

2. Pressure H2- system

< 1.5 bar		stop blow out
< 13.5 bar		separation buffer vessel
> 17.7 bar		blow out
> 19 bar		rupture disk

3. Temperatures Vacuumchamber

> 120 C	RESA
---------	------

4. Pressure Vacuum systems (Vacuum I and II)

> 1E-4 mbar		stop ion pump
> 0.1 mbar		stop He cooling plant
> 1.6 bar	RESA	separation buffer vessel
		reduction H2 pressure to 1.6 bar
> 2.0 bar		rupture disks

5. Pressure Helium systems (Helium I, II and III)

< 1.2 bar		alarm
< 1.1 bar		stop cooling plant
> 2 bar		rupture disk (He I and III)
> 2.3 bar		rupture disk (He II)

Tab.3 Safety actions of CNS control

The shutdown of the reactor by RESA (SCRAM) signals is not necessary to protect the reactor. The reason is to stop nuclear heating of the CNS in order to prevent severe damage of the expensive inpile parts of the CNS.

The commercial cooling plant has its own control computer for the start, steady state and stop procedures. All actions with the cooling plant and the CNS- systems are automatically registered on a printer.

The main data of the CNS are collected on the central computer of the reactor. The data curves as well as the flow diagrams for the different CNS- systems can be observed on color screens in the control rooms of the CNS and the reactor.

6. COLD NEUTRON EXPERIMENTS

The cold neutron experiments are concentrated in the neutron guide hall (Fig.6)

Fig. 6

Experimental
facilities at
the 10 MW BER-II

In the neutron guide hall, 5 cold neutron experiments

- V1. Membrane Diffractometer
- V2. 3-Axis-Spectrometer for CN (FLEX)
- V3. 4-Chopper time-of-flight Spectrometer (NEAT)
- V4. Small-angle-scattering Spectrometer (SANS 1)
- V5. Spin-Echo-Spectrometer (SPAN)

and 2 irradiation experiments are going to be installed

- B6. n, α Depth profile experiment
- B7. Activation of paintings

The planing for additional instruments is in progress.

7. REFERENCES

- /1/ Hahn-Meitner-Institut, "Sicherheitsbericht für den 10 MW Betrieb des Forschungsreaktors BER-II", 3. Fassung, August 1982
- /2/ TECHNICATOME, "Final Study Report, Horizontal Cold Source, HMI- BER II Reactor", Technical Note 21.6.82
- /3/ K. Hansen, K.Jensen, J.A.Leth, J.S. Olsen, K. Stendal, "Preliminary Study of a Cold Neutron Source for the BER II Reactor", Risø Nat. Lab. Nov. 1982
- /4/ A. Axmann, K. Gobrecht, "Die Wahl des Moderators für die Kalte Neutronenquelle des BER II", HMI-B 479, Juli 1984
- /5/ Hahn-Meitner-Institut, "Sicherheitsbericht KNQ BER-II, Kalte Neutronenquelle, Stopfen, Konisches Strahlrohr", 5. Fassung, Februar 1987
- /6/ M. Steiner (ed.), "Projektierte Instrumentierung des Forschungsreaktors BER-II", HMI-B 452, August 1988

The Cold Neutron Source at the FRJ-2 in Jülich

G.S. Bauer

PAUL SCHERRER INSTITUTE

CH 5232 Villigen-PSI, Switzerland

and

KFA Jülich

D 517 Jülich, Germany

ABSTRACT

The paper describes design, operating conditions and performance data of the H₂-cold neutron source at the FRJ-2 in KFA Jülich. A comparison is given between the original version installed in 1969 and a revised one in operation since 1987.

1 INTRODUCTION

The decision to design and build a cold neutron source in Jülich was taken in 1964, only 2 years after the two research reactors at KFA became operational. The cold source was to be installed in a 10 inch horizontal beam tube at the DIDO-type reactor FRJ-2. The installation of the cold source in the reactor took place in 1969. It was complemented by the construction of a neutron laboratory external to the reactor building into which the cold neutrons were transported by means of neutron guides. Both, the cold neutron source and the neutron guides were fabricated and commissioned by in house staff at KFA.

The first suite of four instruments on the cold source became operational in 1971 and have triggered a successful development in the use of cold neutrons at KFA and elsewhere, in particular at the HFR Grenoble.

Paper presented at the International Workshop on Cold Neutron Sources
March 5 - 8, 1990 Los Alamos NW, USA

2 DESIGN CONSIDERATIONS

Given the fact, that the cold source had to be inserted into a beam hole with 10 inches diameter radial to the reactor core, the desire to extract a $10 \times 10 \text{ cm}^2$ cold neutron beam imposed severe boundary conditions on the design of the cold source plug.

Since the dimensions of the beam tube limited the outer diameter of the cold source insert to less than 26 cm allowing for the wall thicknesses of the vacuum jacket and its cooling system as well as the cooling layer around the cold source itself, the diameter of the moderator vessel (144 mm) could only just match the diagonal width of the $10 \times 10 \text{ cm}^2$ neutron beam channel. This required a moderator material with very high slowing-down density. Hence, liquid hydrogen was chosen. The layer thickness was fixed to 5.5 cm, yielding a moderator volume of about 1 liter.

For safety reasons all the liquid hydrogen was to be contained in the beamhole insert, where a protective helium barrier and vacuum jacket were provided. This meant that no pumped system was feasible and a concept where the condensation of the evaporating hydrogen took place right inside the beam tube had to be selected. It proved not possible to achieve a completely filled moderator chamber simply by cooling its cylindrical surface with liquid helium at a reactor power of 25 MW where the heating by neutron moderation and γ -radiation was expected to be 1.2 W/g in aluminium and 4.2 W/g in liquid hydrogen. Any increase of heat transfer surface in the region of the moderator chamber would also increase the nuclear heating such that part of the heat had to be removed by evaporation of hydrogen. This means that a sufficiently large cold surface outside the liquid is required to enable the condensation of the vapor produced, or, in other words, the vessel could be only partly full.

In this situation it was decided to move part of the liquid volume back into the beam tube by 1.2 m where the diameter widened and a condenser with finned tubes could be mounted in a region where the heat generation was down to 0.2 % of what it is at the position of the moderator volume.

3 THE THERMO-SIPHON

A schematic representation of the thermo-siphon is shown in Fig. 1. Its layout is governed by the condition that the buoyancy force of the warm leg relative to the cold leg must overcome the frictional losses in the connecting pipes.

With $\bar{\rho}$ and $\Delta\rho$ being the average density and the density difference of the warm and cold liquid, l and d the length and diameter of the connecting tubes, w the velocity and ξ the coefficient of friction of the flowing liquid in the tubes, the necessary difference in level z of the free surface in the condensor over the highest point of the moderator vessel is given by

$$g \cdot z \cdot \Delta\rho = \bar{\rho} w^2 \xi \cdot l / (2d)$$

Fig. 1 Schematic representation of the cold neutron source arrangement at the FRJ-2 (from /1/).

Fig. 2 Design of the moderator chamber of the cold source on the FRJ-2 (after /1/).

and the necessary mass flow $\dot{M}$ to remove the heat deposited at a rate $\dot{Q}$ in a liquid of thermal capacity c and a temperature rise $\Delta \vartheta$ is

$$\dot{M} = \frac{\dot{Q}}{c \cdot \Delta \vartheta}$$

Since the mass flow in the pipes is given by

$$\dot{M} = \left(\frac{d}{2}\right)^2 \pi \cdot \bar{\rho} \cdot w$$

the two equations can be combined to yield

$$\dot{Q} = \pi \cdot c \cdot \Delta \vartheta \left(\frac{d^5 \cdot z \cdot g \cdot \bar{\rho} \cdot \Delta \rho}{8 l \xi} \right)^{1/2}$$

Due to the mutual interdependence of $\Delta \vartheta$, $\Delta \rho$, $\bar{\rho}$ and ξ , this equation can only be solved iteratively.

The special situation in the beam channel 10H allowed a tube diameter $d = 2$ cm which led to a required minimum level difference z of 2.5 cm, if essentially only the heat deposited in the liquid hydrogen was to be removed. In order to ensure this to the best possible degree, direct cooling of the cylindrical part of the moderator vessel with liquid He was retained.

The design of the moderator vessel is shown in Fig. 2. It is built up of three pieces, two of which form the front (convex) and back (concave) head of the vessel, each including one half of the cylindrical wall with grooves to guide the flow of liquid helium. The third part is just a cylindrical tube pushed over the moderator vessel and welded tight to form the outer walls of the helium flow channels. Inlet and outlet tube stubs are integrated in the back head of the moderator vessel. This design ensures that only one weld on the hydrogen containing vessel is necessary despite its complicated shape and two welds to seal the helium jacket. Keeping the wall thickness down to 2 mm (3 mm for the concave back head) made it possible to limit the weight of the moderator vessel to less than 850 Grams.

The heat exchanger (condensor) of the thermo-siphon is built up of nine finned aluminium tubes with a total surface of 3000 cm² through which cold helium is flown to remove the heat from the hydrogen. Metal bellows in the tubes connecting the condensor to the moderator vessel are provided to accommodate the difference in thermal expansion relative to the one through which the liquid helium flows, especially during the cooling-down and warm-up phases.

4 OPERATING CONSIDERATIONS

During operation thermal insulation of the cold parts is provided by an insulating vacuum and a special design of the support spacers between the warm and cold part of the system which, under internal heating due to radiation, ensure zero heat flux between the warm outer tubes and the cold inner ones.

During initial cooling down, when the H_2 -system is filled with gaseous hydrogen at a pressure around 2 bars, liquid helium is flowed through the condenser and the moderator vessel cooling channels. As condensation of the hydrogen starts, the pressure in the 2000 liter supply tank outside the reactor hall starts to drop and the system pressure can be used as a sensitive measure for the degree of filling of the moderator system.

After the moderator system has been filled, the reactor can be started. As the reactor power and consequently the heat deposition in the liquid hydrogen increases, circulation in the thermo-siphon sets on, with the system completely filled with liquid and operating in a subcooled mode up to a reactor power of 16 kW. At this point evaporation sets on and the system starts to work in a mixed phase mode. The diagram of Fig. 3 shows this situation. It should be noted, however, that the amount of heat transported by evaporation is not a direct measure for the degree of filling of the moderator vessel but rather for the liquid level in the heat exchanger. At 23 MW the heat exchanger is still 1/3 filled with liquid, providing a sufficient margin for subcooling of the liquid.

For the warm-up of the source, the supply of cold helium is stopped and the hydrogen starts to evaporate due to the continuing heat influx.

Fig. 3 Operating conditions in the thermo-siphon as a function of reactor power (from /2/).

5 SAFETY CONSIDERATIONS AND SYSTEM CONTROLS

There are mainly two risks against which the installation has to be guarded: explosion of a hydrogen-air mixture and overheating of the moderator vessel when the reactor is on and the cold source is not operating. Measures taken against the second one are twofold:

1. In order to avoid excessive heating of the moderator vessel after the hydrogen is gone, the insulating vacuum is broken by helium gas to establish a thermal contact to the vacuum jacket. The latter is equipped with a heavy water cooling system arranged in such a way that the strong spatial variation of heat generation is accounted for. This can be seen on Fig. 4 showing the cold source insert before installation. The water flow rate in this system is adjusted to (a) provide enough cooling to remove all heat and (b) avoid freezing of the D₂O in the tubes in case of a reactor shut down with simultaneous flooding of the vacuum space.
2. The temperatures of the moderator vessel and vacuum jacket are continuously monitored with several levels of warning, up to an automatic reactor scram if the maximum allowable limits (180 °C on the moderator vessel, 100 °C on the vacuum jacket) are reached.

There are basically two ways to guard against the risk of a hydrogen-oxygen explosion:

1. to design a vessel strong enough to withstand the resultant pressure
2. to avoid any possible contact of the hydrogen with oxygen or air

Fig. 4 The cold source beamhole insert prior to its installation in the reactor. At the left the vacuum jacket with the D₂O cooling tubes welded onto it can be seen (from /3/).

Fig. 5 Simplified schematic of the cold source supplies system (from /4/).

While the first solution is technically simpler, it has severe disadvantages with respect to the neutronics of the source because the necessarily rather thick walls of the vacuum vessel lead to increased heating of the moderator and to strong absorption especially of the cold neutrons. For this reason the second solution was adopted in Jülich: the whole vacuum system and, by the same token, the whole cold part of the system are surrounded by a helium barrier to make sure there is no way that oxygen could freeze on the cold parts of the system and, in conjunction with a leak in the hydrogen containment, could lead to an explosive mixture upon warm-up. A very much simplified schematic of the various circuits is shown in Fig. 5. It can be seen that the penetrations of the cold helium ducts as well as the hydrogen gas pipe are designed such that the helium barrier forms a perfect enclosure. The helium barrier also surrounds the shutoff-valves and pressure gauges of the vacuum system. The hydrogen gas tube connecting the cold part to the storage volume outside the reactor hall is double walled and the annular space is continuously monitored for hydrogen from possible leaks in the inner tube.

The functions of the control system are based on an extensive safety and risk analysis where all actions necessary to bring the facility into a safe state under all conditions have been identified. More details on the design and instrumentation of the Jülich cold source can be found in refs. /1/, /2/, and /4/ to /7/.

6 NEUTRON EXTRACTION

As mentioned before, the cold neutrons are extracted through a $10 \times 10 \text{ cm}^2$ channel in the centre of the cold source plug (see Fig. 6a). Due to the direct line-of-sight on the reactor core, filters against γ -radiation and fast neutrons are required. Based on an extensive analysis of possible filter arrangements /8/, single crystals of bismuth with their [111]-axis parallel to the beam axis were selected. The total length of 60 cm was originally subdivided. One piece of 12 cm length cooled by the liquid helium was located right below the hydrogen condenser, thus forming part of the inner cryogenic part of the cold source plug. This inner part is bolted to the outer shielding part which, in its initial design, contained a lead shutter and the outer 40 cm long bismuth filter cooled by liquid nitrogen. The spectrum transmitted through these filters is shown in Fig. 7. It can be seen that, due to the [111]-orientation of the single crystals a virtually unperturbed spectrum for wavelengths above $4 \text{ \AA}$ is transmitted. (The dip at $5.6 \text{ \AA}$ results from the set of monochromator crystals of a time of flight spectrometer which was in place further upstream when the spectrum was measured). In the region, where Bragg dips prevail, the different temperatures of the two filters are a disadvantage since they lead to an apparent broadening of the dips and hence excessive reduction of intensity.

7 SOURCE PERFORMANCE

The performance of the source under various operating parameters was studied extensively in 1974, when the reactor power was increased from 15 to 23 MW /5/. The gain factor (intensity with moderator vessel filled relative to moderator vessel empty) measured for both power levels is shown in Fig. 8. The higher gain at 23 MW is an indication for the

Fig. 6 Simplified vertical cut through the beamhole insert of the cold neutron source at the FRJ-2.

- (a) Original version with lead shutter and divided Bi-filter (from /5/).
- (b) Modified version installed in 1985 (from /3/).

Fig. 7

Neutron spectrum transmitted through 52 cm of [111]-oriented Bi-crystals. The marked dip at about 5.6 Å is due to a set of monochromator crystals of a TOF-spectrometer installed upstream of the measuring position (from /5/).

Fig. 8

Measured gain factors (moderator vessel filled relative to moderator vessel empty) of the 5.5 cm thick cold source at 15 and 23 MW reactor power (from /5/).

moderator vessel being thicker than optimum and the bubble fraction at the higher power level counteracting this deficiency to some extent. Further evidence for this to be true was found, when a mixture of D₂ and H₂ at various concentrations was used, as shown in Fig. 9. At a reactor power of 15 MW (Fig. 9a) a significant gain was found by adding up to 20 % of D₂ to the H₂. The apparent levelling off of the curves in the range between 20 % and 40 % is in fact a rather broad maximum, where reduction of absorption seems to be counterbalanced by poorer moderation. This was confirmed at a reactor power of 23 MW (Fig. 9b) where the whole range of concentrations from 0 to 100 % D₂ was examined in two runs. (The fact, that this curve drops below 1 at high concentrations is of course due to the H₂-filled vessel being the reference, not an empty one).

Factoring the maximum gains obtained at the two power levels at 4.4 Å (1.27 at 15 MW and 1.2 at 23 MW) into the absolute gain values at 4.4 Å shown in Fig. 8 (9.4 and 10 respectively), the product is the same in both cases, showing that the net effect of adding D₂ is the same as reducing the density by bubbles.

It deserves mentioning in this context, that the gains shown in Fig. 9a are significantly higher for short wavelengths than for long wavelengths, in contrast to what one would expect if reduction of absorption were the dominating effect. This indicates, that no thermal equilibrium is reached near the surface of small H₂-cold sources.

Based on these results, the source was operated with an admixture of 20 % D₂ from 1975 on.

The instruments served by this cold source and its neutron guide system have been described in a series of articles (/9/ to /14/).

8 RECENT IMPROVEMENTS

After 12 years of successful operation a major rebuild of the whole neutron guide system and a substantial extension of the external neutron laboratory were undertaken. In this context also the cold source insert in the reactor was replaced by a newly built one. This provided the opportunity to incorporate some of the experience of the past without introducing any major changes in the concept. The new cold source plug is shown in Fig. 6b. The main improvements were the following:

- The thickness of the moderator vessel was reduced from 5.5 to 4 cm.
- The entire bismuth filter was moved to the inner part of the plug and is now helium cooled.
- The lead shutter in the plug was omitted.
- The front end of the neutron guides was moved right up to the end of the filter.
- A new system of neutron guides with polished glass plates and coated with 58-Ni was provided.

Fig. 9 Effect of an admixture of D₂ to the H₂ in the case of the 5.5 cm thick moderator vessel (from /5/)

(a) Reactor power 15 MW

(b) Reactor power 23 MW

Each one of these measures had a positive effect on the overall performance of the system, with the result, that compared to the final state of the old system, where some degradation had already taken place, a gain of a factor of 3.6 in overall intensity was obtained at the position, where the neutron guides leave the reactor hall /3/.

9 REFERENCES

- /1/ C. Doose, A. Preussner, F. Stelzer, H. Stiller and A. Tholen:
"The Cold Neutron Source in Jülich", Cryogenics, April 1971, pp. 107 - 113
- /2/ F. Stelzer:
"Thermodynamic Design of the Cold Neutron Source at the Reactor FRJ-2",
Kerntechnik 13 (1971), pp. 534 - 539
- /3/ J. Duppich and K. Werner:
"Das externe Neutronenlabor ELLA am FRJ-2 der KFA Jülich", Report
Jül - 2263 (1989)
- /4/ C. Doose and A. Tholen:
"Construction and Operation of the Cold Neutron Source at the Reactor FRJ-2",
Kerntechnik 13 (1971), pp. 539 - 549
- /5/ G. Bauer, A. Zinken, A. Tholen:
"Strahlqualität und Betriebsverhalten der Kalten Neutronenquelle mit Neutronen-
leiter am Forschungsreaktor FRJ-2 (DIDO), Report Jül - 1075-FF (1974)
- /6/ A. Preussner:
"The Instrumentation of the Cold Neutron Source at the Reactor FRJ-2", Kern-
technik 13 (1971), pp. 550 - 552
- /7/ W. Koepe, H. Leyers:
"Temperature Measurements in the Cold Neutron Source at the Reactor FRJ-2",
Kerntechnik 13 (1971), pp. 553 - 556
- /8/ G. Bauer and H. Seyfarth:
"Die Eignung von MgO-, SiO₂- und Bi-Einkristallen oder Quasieinkristallen als Fil-
ter für subthermische und thermische Neutronenstrahlen hoher Intensität", Atom-
kernenergie 18 (1971), pp. 236 - 246

- /9/ G. Bauer, G. Joswig, J. Schelten, W. Schmatz:
"Neutron beam guide and external neutron laboratory of a cold neutron source",
Kerntechnik 14 (1972), pp. 9 - 12
- /10/ R. Stockmeyer:
"Time of flight spectrometer for slow neutrons", Kerntechnik 14 (1972)
pp. 13 - 14
- /11/ B. Alefeld:
"Neutron back scattering spectrometer", Kerntechnik 14 (1972) pp. 15 - 17
- /12/ H.H. Schmidt:
"High resolution triple axis neutron spectrometer", Kerntechnik 14 (1972)
p.p. 17 - 19
- /13/ G Bauer:
"Disorder spectrometer for measuring diffuse neutron scattering", Kerntechnik 14
(1972), pp. 20 - 21
- /14/ G. Bauer:
"Neutron back scattering at high Doppler velocities for measuring differences in
lattice parameters", Kerntechnik 14 (1972), pp. 82 - 85
- /15/ J. Schelten:
"The small angle scattering facility at the bent neutron guide of the cold neutron
source at the reactor FRJ-2", Kerntechnik 14 (1972), pp. 86 - 88

REACTOR COLD SOURCES IN JAPAN

Masahiko Utsuro
Research Reactor Institute, Kyoto University
Kumatori-cho, Sennan-gun, Osaka JAPAN

Hidetake Takahashi
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki JAPAN

ABSTRACT

The developments history and the present status of reactor cold sources in Japan are reviewed as well as the descriptions of the existing two reactor cold sources, one is the first cold source in Japan inserted and operated since 1987 at Kyoto University Reactor (KUR), and the other, JRR-3 cold source, is expected to start operation before this summer.

I. INTRODUCTION

The early studies on cold neutron sources in Japan were mainly concerned on the neutron moderating mechanisms in low temperature materials and experimental comparisons of these performances by reactor physics researchers. Variations of neutron spectra in low temperature ice,⁽¹⁾ solid methane,^(2,3) solid mesitylene⁽⁴⁾ as an effective cold moderator with low temperature moderating mechanism,⁽⁵⁾ and in liquid hydrogen moderators were investigated experimentally. Further, theoretical analyses of the effective neutron temperatures in these cold moderators were carried out

based on the neutron scattering formulae in condensed matters.^(6,7) Concerning liquid hydrogen and deuterium, rather special theoretical analyses were necessary with taking into considerations of their molecular motions and neutron scattering properties, as described in the next Chapter.

Furthermore, in the course of these experimental studies on the cold moderators, the cryogenic handling and the safety considerations were also experienced to a certain extent.

Thus, these fundamental studies on cold sources were developed later to the realizations of various cold neutron source facilities in our country with solid methane,⁽⁸⁾ solid mesitylene⁽⁹⁾ and with liquid hydrogen/deuterium moderators.⁽¹⁰⁾ Further, due to the possible uses of solid heavy water as cold moderator,⁽¹¹⁾ neutron scattering properties of heavy ice were also studied at low temperatures.⁽¹²⁾

In the following Chapters, among these studies the developments and performances of the reactor cold sources in our country will be described.

II. REACTOR COLD SOURCE DEVELOPMENTS IN JAPAN

The preliminary stage for the design study of the reactor cold source in Japan was the neutron scattering analyses applicable to the cold moderators of liquid hydrogen and deuterium. In order to prepare a computer calculation program simple enough to enable the various parametric studies including on moderator sizes and geometries and at the same time effectively sophisticated to describe the characteristic features in the scattering phenomena in these liquid materials, the synthetic kernel approach by Egelstaff and Schofield⁽¹³⁾ was employed as the starting point, and it was further extended to take into considerations of the intermolecular excitations in the liquid hydrogen.⁽¹⁴⁾ A computer code based on these analytical equations was prepared. The calculated results with this code for the total cross sections, differential scattering cross sections and neutron spectra in the liquid hydrogen moderator gave reasonable agreements with the experimental results.

The code was furthermore extended to include the intermolecular interference effects which play important role in the low energy scattering in liquid para-hydrogen and in liquid deuterium.⁽¹⁵⁾ In this code, the interference effects are introduced with the convolution approximation, and the calculated results explain in the reasonable extent the characteristic features measured in the low energy region of the neutron scattering in these liquids.

In these periods of cold source developments in our country, also attained are the experimental experiences of handling liquid hydrogen and deuterium in reactor sites or in a thermodynamic flowing loops, both of which are necessary steps for the developments of reactor sources. That is, neutron scattering experiments with these liquids,⁽¹⁵⁾ various exercises by the KUR staff attending the development experiments for the H-1 space rocket engine at an industrial company in Japan, and the developments and various test experiments with an out-of-pile closed thermosiphon liquid hydrogen loop in KUR laboratory⁽¹⁶⁾ are some parts of these preparations. The tests with the thermosiphon loop included studies on flooding phenomena in the early stage of the hydrogen condensation in the loop, the frequency response of the loop by using heat load variations, and the effect of the working pressure to the system stability.

As the result of these development studies on liquid hydrogen and deuterium loops, sufficient experiences and preparations were obtained at KUR for the actual construction of the first reactor cold source in Japan.

III. KUR DEUTERIUM COLD SOURCE

3.1 Fundamental Structures^(10,17)

From several reasons in the fundamental considerations on the place inserting the KUR-CNS such as the higher thermal neutron flux, easy extractions of the produced cold neutrons, well decreased γ -rays from the core due to the existense of 20 cm thick lead thermal shielding, the graphite thermal column was chosen as the place of the CNS, and these arrangements are shown in Fig. 1. Further,

PLAN

VERTICAL SECTION

No	Item
1	Condenser
2	Moderator transfer tube
3	Cold moderator cell
4	Earthquake-proof platform
5	Mobile shield of heavy-concrete
6	Fixed graphite
7	Movable graphite
8	Cold beam hole
9	Pneumatic tube
10	Thermal beam hole
11	Long-time irradiation hole

Fig. 1. KUR deuterium cold source inserted in the modernized graphite thermal column

for producing the higher cold neutron flux in a medium size cold moderator of several litres, a mixture liquid of 90% deuterium and 10% hydrogen is employed in our cold source of KUR according to the numerical analyses studies on various mixture ratios.

As for the materials of the moderator cell and the transfer tubes inserted into the graphite assembly, aluminum alloy A5052 is employed mainly from the viewpoints of low neutron absorption, low activation, high mechanical reliabilities free from stress corrosion at the working temperatures and the good welding properties. The whole of these parts including the deuterium condensor were made as a single machine with welding. For the design of the thin-walled smooth shape moderator cell shown in Fig. 2, the nuclear heating measurements of aluminum in the graphite column and the induced stress calculations with the finite element method were carried out. A dummy cell manufactured simultaneously with the used one was pressure-tested which showed quite satisfactory results on the strength.

3.2 Safety Design^(10,17)

The fundamental concepts of the safety design of the KUR-CNS are; the completely closed and vacuum-tight system with welding for the

Fig. 2. Internal structure of moderator chamber part of KUR-CNS

most parts, helium-neon gas barrier for low temperature deuterium systems, so-called 2-out-of-3 systems for important instrumentations and careful impurity and leak monitorings with gas analyses by gas chromatographies and mass spectroscopies. The schematic flow diagram of the KUR-CNS is illustrated in Fig.3.

The evacuation of the system for thermal insulation is started with a turbo-molecular pump, and later closing the valve at the refrigeration stage, an ion pump is actuated for the long-term evacuation

Fig. 3. Schematic flow diagram of KUR-CNS

of the out-gas.

A number of tests and inspections were performed in the each stage of out-of-pile set-up, various kinds of out-of-pile test operations, in-pile re-constructions and the final in-pile test operations including the rated reactor operations, and all the results were satisfactory passing the authorized tests by the STA inspectors.

3.3 Neutron Measurements⁽¹⁸⁾

The energy spectra and the intensity of neutrons emerging from the cold moderator cell were measured with the time-of-flight method as shown in Fig. 4. In the measurements, direct γ -rays and fast neutrons from the reactor core were separated by reflecting cold neutrons on a supermirror. For deciding the starting channel in the time-analyzer, several orders of Bragg reflections from a pyrographite specimen were used. The very cold neutron spectrum was also measured with a very slow chopper and a guide tube flight path.

These measurements were repeated for the both conditions of liquid hydrogen and liquid deuterium moderators. The cold neutron gain factors and the spectra derived from these results and those without the cold source operation are shown in Figs. 5-7. The absolute neutron intensity at the exit of the beam hole in the condition of liquid hydrogen operation is listed in TABLE I. Measurement on the mixture moderator as expected in the design calculations will be considered in future.

IV. JRR-3 COLD NEUTRON SOURCE

4.1 Basic Status

JRR-3 Cold Neutron Source (JCNS) is planned to be installed to the new JRR-3 in Japan Atomic Energy Research Institute (JAERI) as one of the main purposes for the modification of it. The modification work started in 1984, and the critical of the new

TABLE I
KUR-CNS NEUTRON INTENSITY
FROM BEAM HOLE FOR COLD
GUIDE TUBE

(x10 ⁹ n/cm ² s Å sterad)		
	CNS-ON	CNS-OFF
1 Å	49.0	277
2	85.2	51.6
3	56.0	11.1
4	35.3	3.2
5	20.6	1.2
6	10.7	0.44
7	5.73	0.31
8	3.13	0.15
10	1.11	
12	0.49	
14	0.20

Fig. 4. Experimental arrangement for the time-of-flight measurements of cold neutron spectra of KUR-CNS

Fig. 5. Measured cold neutron spectra for CNS-ON and -OFF in the case of liquid deuterium moderator

Fig. 6. Measured cold neutron gain factor (CNS-ON/CNS-OFF) for liquid deuterium moderator

Fig. 7. Measured cold neutron gain factor (CNS-ON/CNS-OFF) for liquid hydrogen moderator

reactor will be attained on March, 1990. The conceptional design of JCNS was started at 1982 by referring to the ORPHEE CNS that was the suitable type for the new JRR-3 considering the reactor power, neutron flux, generating radioactivities, the simple construction and so on. The JCNS will be started to operate in 1990 together with the new JRR-3. The safety design, and the confirmation tests are described here for JCNS.

4.2 Outline of JCNS

The JCNS consists mainly of two parts as shown in Fig. 8. One of them is the hydrogen circuit that consists of the condenser with cryopump and rupture disk, the buffer tank, the cold transfer tubes, the vacuum chamber and the moderator cell which contain hydrogen gas or liquid. Another is the helium refrigerator system for supplying low temperature helium gas of 15K to the condenser, consisting of compressors, heat exchangers, expansion turbines, control heater etc. The hydrogen circuit is in the reactor hall, and the helium refrigerator system is in the compressor building which is about 60m far from the reactor building in order to make space and avoid the vibrations by compressor affecting to beam experiments. The outlet of the expansion turbine is connected to the inlet of the condenser by the low temperature tube with vacuum insulation, and the distance is about 70m. The schematic flow diagram of JCNS is shown in Fig. 8.

4.3 Safety Design of JCNS

The design of JCNS has been referred to ORPHEE CNS, but there are some differences between JCNS and ORPHEE CNS, and several tests have been made for the confirmation of the safety and performance at the design condition.

Design Principle on JCNS

(1) Materials of main components are to be selected in consideration of the strength, corrosion resistance, irradiation resistance, and low permeability for hydrogen. Especially, for the moderator cell, the material should have good performance in the high irradiation and the very low temperature conditions: A286 is used for the material of the moderator cell, because of its good performance

Fig. 8. Schematic flow diagram of JCN-5

for the severe irradiation condition in low temperature, and high strength. On the other hand, the low temperature irradiation data seem to be limited until around 1×10^{19} nvt and not enough to evaluate for JCNS.⁽¹⁹⁾ But the ORPHEE CNS has experienced more than 1×10^{20} nvt for A286. The moderator cell of the JCNS is evaluated its lifetime and performance by the data and the experience.

(2) The boundaries for hydrogen are to be made sure without leak even in a vacuum chamber: Basically welding joints are used with careful inspection except for one flange joint for exchanging the moderator cell.

(3) All the hydrogen components are to be set in the water so that hydrogen does not meet with air: A subpool is prepared just beside the reactor pool. All the hydrogen containers are set in the subpool and the reactor pool, and the water level of them are always watched during containing the hydrogen.

(4) The components in the reactor pool should not fail to prevent any influences for the reactor soundness even if the hydrogen would react with the air: The vacuum chamber which is set in the heavy water tank and other main components (the cold transfer tube, condenser, buffer tank) are designed with the sufficient wall thickness for 20 kg/cm^2 considering the detonation in the components. The vacuum chamber is made of A6061 by all machining without any welding joints.

(5) If the JCNS has a trouble or accident during the reactor operation, it is to be detected and the reactor is automatically shut down when it makes the hydrogen pressure rise up: The detectors for the hydrogen pressure are set to act for the reactor shut down as one-out-of-two system as well as the important reactor system. On the other hand, an alarm signal is prepared for the vacuum pressure, thus the operator can make the reactor shut down by the alarm signal based on the judgement on the system situation because most troubles in the vacuum layer lead the hydrogen pressure to rise up.

(6) The thermal oscillation is to be avoided to happen during the reactor operation: It is clear by the thermosiphon test that the thermal oscillation can be happened depending on the quantity of liquid hydrogen and thermal input in the hydrogen circuit in the

case of thermosiphon typed CNS. In JCNS, it is proper to avoid the thermal oscillation that the initially charged hydrogen gas pressure is about 3.5kg/cm^2 abs. and the quantity of liquid hydrogen is about 1.6 l at the operation pressure of 1.2kg/cm^2 abs..

Confirmation Tests for JCNS

Many kinds of tests were performed to confirm the safety and performance of JCNS.

(1) Mechanical strength test for the moderator cell: The moderator cell is required to be thin walled and special shape like a canteen with oval cross section. Therefore, the mechanical strength was tested for the moderator cell by means of internal and outer pressure, and the results were good agreement with the calculated one by the three dimension finite element code ADINA. The strain distribution is shown in Fig. 9.

Some main results are: i) The external strain is not recognized at the 4.75kg/cm^2 of internal pressure. ii) The increment of the strain according to pressure cycles is not recognized until the number of 1000 cycles. iii) No collapse occurs at the outer pressure of 2.0kg/cm^2 . iv) The collapse occurs at 32kg/cm^2 and the leakage begins at 195kg/cm^2 of internal pressure.

(2) $\text{O}_2\text{-H}_2$ reaction test: It was tested by using the same scale and material model as the actual that the pressure boundaries were not failed when the $\text{O}_2\text{-H}_2$ reaction as a hypothetical condition in JCNS occurred in the components. In this test, the detonation that is the severest phenomenon of $\text{O}_2\text{-H}_2$ reaction was supposed to take place in the test hydrogen circuit in order to measure the exerted pressure on the components and their strain, deformation, etc..⁽²⁰⁾

(3) Thermosiphon test: An experimental study has been performed to understand the characteristics of the closed type thermosiphon with concentric tubes by using Freon-113 as working fluid on the full scale model.⁽²¹⁾ This experiment was undertaken for observing flow pattern of the working fluid, and measuring the heat transfer limitation, the liquid level and void ratio in the moderator cell as a function of the charged liquid volume and thermal input by using a glass model.

As the results, the following main items are made clear: i) The

Fig. 10. Stored condition of liquid hydrogen in moderator cell

Fig. 9. Strain distribution by pressure test for moderator cell

volume of the charged liquid is very important factor to prevent the thermosiphon oscillation and dryout. If the volume of the charged liquid is more than the critical volume which depends on the size, shape and volume of the thermosiphon circuit, the oscillation and dryout phenomena may not occur. ii) The volume of stored liquid and void ratio in the moderator cell are controlled by regulating the volume of the charged liquid. These results show that the thermosiphon in the JCNS can be controlled properly by adjusting the volume of the charged liquid. Furthermore, these results are confirmed again in the out-of-pile tests using the actual components and hydrogen as shown in Fig. 10.

V. FUTURE DEVELOPMENTS

Cold sources of liquid deuterium and hydrogen are much effective devices not only for giving cold neutron flux increase, but also for providing considerably enhanced very cold neutron (VCN) flux which is further used for ultracold neutron (UCN) production. Considering from the expected future developments of various kinds of VCN and UCN experiments, further studies on the efficient VCN source for reactors will become important task. In this sense, a new proposal of the very cold moderator of solid deuterium or solid hydrogen inserted in a medium power reactor⁽²²⁾ would be analyzed and developed further. Another special source of super-thermal helium UCN converter is also studied as a collaboration of KUR and KEK in our country.

VI. REFERENCES

1. K.Inoue, "Slowing down of neutrons to very low temperature by cold solid hydrogenous moderators", J. Nucl.Sci.Technol., 7[11], 580(1970).
2. K.Inoue, N.Otomo, M.Utsuro and Y.Fujita, "Slow neutron spectra in the liquid and solid methane", ibid., 9[6], 374(1972).
3. K.Inoue, N.Otomo, H.Iwasa and Y.Kiyanagi, "Slow neutron spectra in cold moderators", ibid., 11[5], 228(1974).
4. M.Utsuro, M.Sugimoto and Y.Fujita, "Experimental study on a cold neutron source of solid methylbenzene", Ann.Rep.Res.React. Inst.Kyoto Univ., 8, 17(1975).
5. M.Utsuro, "A simple neutron scattering study of proton motion in methyl compounds", J.Phys.C:Solid State Phys., 9, L171(1976).

6. M.Utsuro, "A simple relation for effective neutron temperature in cold moderators with lattice vibrational modes", J.Nucl.Sci. Technol., 10[7], 428 (1973).
7. M.Utsuro, "Simple expression for effective neutron temperature due to rotational motions of cold-moderator molecules", ibid., 11[10], 434 (1974).
8. S.Ikeda, Y.Ishikawa and K.Inoue, "KENS cold neutron source", Proc.ICANS-IV, 200 (1981).
9. M.Utsuro and K.Okumura, "Production and guide tube transmission of very cold neutrons from pulsed cold source", J.Nucl.Sci.Technol., 19[11], 863 (1982).
10. M.Utsuro, T.Kawai, Y.Maeda, H.Yamaoka, T.Akiyoshi and S.Okamoto, "Liquid deuterium cold source in graphite thermal column", Physica, 156&157B, 540 (1989).
11. R.S.Carter and T.M.Raby, "The National Bureau of Standards Reactor (NBSR)", Proc.Symp.Use and Development of Low and Medium Flux Research Reactors, Supp.Kerntechnik, Vol.44, 180 (1984).
12. M.Utsuro and N.Morishima, "Total neutron cross section in heavy ice at 77 and 15K for neutron energies between 0.3 and 100 meV", J.Nucl.Sci.Technol., 18[9], 739 (1981).
13. P.A.Egelstaff and P.Schofield, "On the evaluation of the thermal neutron scattering law", Nucl.Sci.Eng., 12, 260 (1962).
14. M.Utsuro, "Slow neutron scattering and intermolecular excitations in liquid hydrogen", Z.Phys., B27, 111 (1977).
15. M.Utsuro and M.Hetzelt, "Liquid ortho-deuterium as a converter for ultracold neutrons", Neutron Inel. Scatt. 1977 (IAEA, Vienna) Vol.I, 67 (1978).
16. T.Kawai, M.Sugimoto and S.Okamoto, "Cold neutron facility on KUR", Ann.Rep.Res.Reactor Inst.Kyoto Univ., Vol.13, 105 (1980).
17. M.Utsuro, T.Kawai, Y.Maeda, H.Yamaoka, T.Akiyoshi and S.Okamoto, "Installation of a liquid deuterium cold source in an operated reactor thermal column", Proc.Symp.Res.Reactor Safety, Operations and Modifications (IAEA, Chalk River) to be pub. in 1990.
18. T.Ebisawa, T.Kawai, T.Akiyoshi, M.Utsuro, Y.Maeda, K.Yoneda, S.Kawano, S.Tasaki, H.Yamaoka and S.Okamoto, "Neutron intensity measurements from the cold neutron source with liquid hydrogen moderator of KUR", Ann.Rep.Res.Reactor Inst.Kyoto Univ., Vol.21, 1 (1988).
19. Y.Kawabata and H.Takahashi, "Neutron irradiation effects at cryogenic temperature on the structural materials for cold neutron source", JAERI-M86-139 (1986).
20. T.Hibi, H.Takahashi et al., "JRR-3 cold neutron source facility H₂-O₂ explosion safety proof testing", IAEA-SM-310 (1989).
21. T.Kumai, M.Kudo et al., "Fundamental experiment on the closed circuit type thermosiphon with concentric tubes for the JRR-3 cold neutron source (II)", JAERI-M89-114 (1989).
22. M.Utsuro and K.Okumura, "A combined system for the generation of an intense cold neutron beam with a medium power research reactor", Nucl.Instrum.Methods in Phys. Res., A281, 649 (1989).

EXISTING COLD SOURCES AT U.S. REACTORS

J. M. Rowe

National Institute of Standards and Technology
Gaithersburg, MD 20899

D. C. Rorer

Brookhaven National Laboratory
Upton, NY 11973-5000.

ABSTRACT

This report presents the salient design criteria and performance of the existing cold sources installed in the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory (BNL) and the Neutron Beam Split-core Reactor (NBSR) at the National Institute of Standards and Technology (NIST). These two sources are of different design than those installed in European reactors, reflecting design constraints imposed both by the regulatory environment and by the sealed vessel design of the reactors themselves.

I. INTRODUCTION

At the present time, there are two high performance research reactors in the U.S. with installed, operating cold neutron sources - a liquid hydrogen source in the HFBR in Brookhaven National Laboratory (BNL), Upton, N.Y. and a solid D₂O ice source (with 8% H₂O added) in the NBSR at the National Institute of Standards and Technology (NIST), Gaithersburg, MD. The source in the HFBR has been operating for approximately nine years, while the source in the NBSR was first operated in 1987. These sources are briefly described in turn in the following sections.

II. THE COLD NEUTRON FACILITY AT THE HIGH FLUX BEAM REACTOR

Description

The HFBR cold moderator is an ellipsoidal aluminum chamber with a capacity of 1.4 liters of liquid hydrogen; the major and minor axes of the ellipse have dimensions of 20.2 and 7.1 cm, respectively. Hydrogen was chosen over deuterium because of the physical constraint of limited space in the existing reactor design. Hydrogen gas is condensed into the chamber at a pressure of approximately 4 atmospheres at approximately 18 K. At the end of each reactor cycle, or on any upset condition, the hydrogen is vented through a particulate filter into the atmosphere outside of the building. The facility is designed to run unattended, although in practice it is checked at least once every 24 hours by a technician.

Cooling is provided by a 3500-watt helium refrigerator which delivers 150-190 grams/s of helium gas at 16 K to a set of cooling tubes brazed to the outside of the chamber. The heat load on the chamber itself is approximately 700 watts when the HFBR is at full power (60 MW). Another 800 watts is expended in delivering the cold gas from the remotely located refrigerator to the chamber itself, approximately 300 feet away. The remainder of the available refrigerating capacity, which is normally compensated by an electric heater, has been found to be extremely useful to have in reserve, allowing continuous operation of the facility even under conditions of degraded refrigerator performance (arising principally due to contamination of the helium gas with oil and condensable gases over long periods of time).

A major design consideration was the provision for operation of the reactor even in the event that the helium refrigerator becomes completely inoperative. This is accomplished by removing the hydrogen from the moderator chamber and flowing clean nitrogen gas through the interior of the chamber to remove the radiation heat generated by the reactor at full power. Loss of all moderator cooling would cause the temperature of the vacuum-insulated chamber to exceed 300 F in less than 3 minutes, eventually ruining the temper of the aluminum chamber and rendering it useless as a pressure vessel. The nitrogen gas is supplied by evaporating liquid nitrogen stored in two 6000-gallon vessels outside the reactor building. After leaving the chamber, the nitrogen gas is vented through a filter to the atmosphere.

Whenever hydrogen is vented from the moderator, the helium refrigerator is automatically by-passed and a warm helium gas purge of the interior of the chamber is carried out. This is immediately followed by initiation of auxiliary nitrogen cooling flow at 22 cfm. In the event that both the helium refrigerator and the auxiliary cooling are simultaneously inoperative, the reactor will be shut down automatically to protect the moderator from over-heating.

Safety Considerations

One of the principal safety features incorporated into the design of this facility is an inert gas blanket (helium) which surrounds every part of the system containing hydrogen gas. This blanket serves as a barrier to prevent the mixing of hydrogen with air, in the event of a leak developing. The inlet and vent piping leading to the moderator chamber is back-filled with helium after the hydrogen has been sealed into the chamber, completing the isolation of the hydrogen from the air.

After the vacuum space has been initially evacuated by pumping it out to the atmosphere, a high vacuum is maintained around the moderator by pumping on the space with a blower and forepump which are also sealed within the blanket. These pumps discharge directly into the blanket; the blanket pressure is continuously monitored for any pressure buildup outside of its normal 3-4 psig range.

All pressures in these systems (hydrogen, vacuum space, and blanket) are monitored continuously, and if the pressures stray outside of pre-determined limits, a vent-and-purge of the moderator is automatically initiated. To increase reliability, most of these instruments are triply redundant and arranged in a 2-out-of-3 logic to initiate vent-and-purge safety action.

Since the inert blanket design provides assurance that once charged, the hydrogen can be kept pure, it remains to provide equal assurance that the hydrogen as originally purchased meets appropriate purity specifications, and additionally, that no air leaks into the system during the charging process. This is accomplished by:

- 1) Inspections of the vendor's plant during the process of filling BNL's CNF hydrogen bottles which are dedicated solely to this use.
- 2) Independent analysis of randomly selected bottles from each filled batch.
- 3) Use of an on-line trace oxygen analyzer during the hydrogen charging process. This analyzer is capable of detecting 0.2 ppm of oxygen in the hydrogen.

Performance

The experimentally measured gain of the cold moderator is presented in Figure 1. Gain ranges from a factor of 10 at 2.5 meV to a factor of 5.5 at 5 meV.

One of the most important considerations, aside from the flux gain at long wavelengths, is the operating factor for this facility. After the first few years of break-in operation, during which various design and instrumentation improvements were made, we have been able to achieve availability factors greater than 95% over relatively long periods of time. The most significant contributor to forced outage preventing 100% availability has been the momentary interruption of electrical power from the supply mains, due to thunderstorms. (After a vent-and-purge, it takes a

minimum of approximately 4 hours to re-fill the facility.) On several occasions punctuating these periods of relatively smooth operation, unexpected flaws have caused major outages lasting more than a month. These experiences suggest that after nine years, the learning curve for this facility may not yet have approached its asymptotic limit.

Figure 1. Measured gain of HFBR cold source

Training

Training and qualification of operating personnel for this facility continues to be an important consideration in achieving safe and reliable operation. The CNF is now staffed by 4 persons: a facility manager, an engineer, and two technicians. A training and certification program for CNF operating personnel, similar in many respects to the training program for reactor operators, is now in place. In order to maintain their certification as facility operators, the CNF technicians must take a written re-qualification exam every two years, and must have participated actively in the operation of the facility during the interval between examinations.

III. THE COLD NEUTRON SOURCE IN THE NBSR

General Description

The cold neutron source in the NBSR consists of 16 liters of D_2O ice with 8% H_2O added to optimize cold neutron production. The arrangement of the source is shown in Fig. 2, which contains all relevant dimensions.

Figure 2. layout of the cold neutron source in the NBSR

There are several features that should be noted from this figure. The first is the 20 cm diameter by 15 cm deep reentrant hole that increases the cold flux seen by the neutron guides. Although the enhancement provided by this feature cannot be measured, calculations indicate a factor of two improvement over the current density that would be seen without it. Second, since the D_2O weighs approximately 16 kg, it was necessary to install a bismuth shield as shown. The first 2.5 cm of this shield consists of radiogenic lead, required to assure adequate thermal conductivity to carry away the large heat load (approximately 1 watt/g). The neutron current density was measured before and after the shield was installed, and the transmission for thermal neutrons found to be 65%. As a result of this shield, the actual thermal load on the moderator is less than 0.04 watts/g, for a total load on the refrigerator system of approximately 800 watts. The source is cooled by gaseous helium at 25 K circulated through coils embedded in the ice. The entire cryostat assembly is made from a magnesium alloy

(ASTM A231B), which is heat treated after assembly to O temper in order to relieve stresses introduced by welding. The useful upper temperature limit of the cryostat assembly is 100 C, requiring that the vacuum chamber be water (heavy) cooled. The third feature (not shown in the figure) is that the port in which the moderator assembly is installed penetrates into the region of highest thermal flux accessible by the horizontal beams, and is vertically centered on the 17 cm unfuelled region of the core. Finally, the very good angular separation of viewing directions allowed by the shield and port geometry is shown by the beginning of the eight guides being installed as part of a general upgrade(the guides are 6 cm wide by 15 cm high).The cold helium gas for cold source cooling is provided by a 1kW turbine expander which delivers 30 g/s of 25-30 K gas to the cooling tubes. Because of the cracking which occurs as the ice is frozen, the moderator assembly is kept under a helium atmosphere to increase the thermal conductivity. In order to prevent reactor shutdowns when this refrigerator fails, an emergency refrigerator with sufficient cooling power to prevent melting of the ice at full reactor power is kept on standby. The large heat capacity of the ice provides over two hours to switch over to this refrigerator before the ice begins to melt. The only system which can cause a reactor scram is the water cooling to the bismuth tip, and in two years of operation, there have been no reactor scrams or shutdowns caused by the cryogenic facility.

The entire cryostat, and all lines that go into it are surrounded by a helium blanket that is continuously monitored for pressure drop and contamination by other gases. In general, ice is made in the cryostat by freezing in layers, and is maintained for three reactor cycles (approximately 16 weeks). During reactor shutdowns, cooling is provided by the emergency refrigerator, which requires no surveillance, and is an extremely simple device that cools helium gas to 100 K.

One feature of the moderator, which is shared with all solid moderators, is the cumulative radiation damage which occurs during reactor operation. In water, the radiation products are essentially hydrogen and hydroxyl ion radicals, which are relatively immobile at 25 K, and the recombination products are primarily water. (The details of the radiation chemistry are complex, and the simple statements made here should not be taken too literally.) During operation, radicals are continuously being formed, and there is also a recombination going on, in spite of the low mobility. In order to prevent a large buildup of radicals, we have established a procedure to raise the temperature of the source by approximately 30 K, which speeds up the recombination. In general, this is done every 48 hours, and requires less than one hour to reestablish temperatures. If this is not done, eventually the process will self-initiate, the source will warm up, and then cool back down. This process is not particularly dramatic, in part because of the cracks in the ice which allow for release of gases which may temporarily form, but largely because of the fact that the recombination product is almost entirely water. The only measureable hydrogen gas releases occur during warming to melt the ice, during which time a helium sweep is maintained to remove gas as it is released from the solid. The rate of release of hydrogen is slow, and the thermal capacity of the ice prevents rapid melting. During any alarm condition on the moderator, the helium sweep is automatically initiated, and continues until

manually reset. Under the conditions of operation of the source, virtually no oxygen is produced or released, although prolonged irradiation at elevated temperatures does produce a limited amount. When the ice is completely melted after three reactor cycles, the water does contain hydrogen (deuterium) peroxide in solution. At no time is any significant quantity of gaseous hydrogen and gaseous oxygen released simultaneously, as a result of the very different diffusion coefficients for the two species in ice. The only hazard presented by the radiolysis of the ice is from oxygen introduced into the system from the atmosphere when gaseous hydrogen is present, and the helium blanket which surrounds the entire moderator assembly protects from this possibility.

Operating History and Performance

The cold source first operated in 1987, and has performed satisfactorily since, except for refrigerator failures. The present refrigerator is of quite old design, and has proven to be the major cause of lost operating time. Spare parts are not easily available, and the mean time to repair is excessive. A new 3.5 kW refrigerator has been ordered, and will be delivered during 1991. This will provide a significant reserve cooling capacity for the present source, as well as providing the cooling for a new source of liquid hydrogen. The only other major problem arose from a faulty operating procedure which resulted in a vacuum failure during reactor shutdown, and subsequent freezing and rupture of the cryostat water cooling lines. The cryostat assembly was replaced with a spare, and operation resumed with minimal lost time.

The neutronic performance of the source has been carefully measured, and studies of the optimum D_2O/H_2O ratio have been performed. The optimum performance is obtained with 8% H_2O , but the maximum is weak and wavelength dependent, so that the exact optimum is poorly determined. Since the cryogenic facility penetrates into the same region as the cold source, and beam tubes were operated from this facility before the source was installed, the performance of the source has been measured as compared to the best beam tube in the reactor, the only relevant measure of performance, if seldom used. By this method of measurement, the neutron flux at 4 Å is increased by a factor of 3 *over that of the best beam tube*. Two other figures are more often quoted for cold source performance - source empty/source full (for H_2), and source full and cold/source full of warm D_2O (for D_2). These two figures for the NBSR source are 5 and 10 respectively at 4 Å. The significant weakness of the D_2O source occurs at higher wavelengths, where the gain does not increase as rapidly as it does for the liquid sources, but saturates at approximately 3.7 times the best beam tube. The characteristic temperature for the source is approximately 65 K for wavelengths greater than 3 Å. As a result of this relatively poorer performance at long wavelengths, the ice source will be replaced by a liquid hydrogen source in the near future.

IV. SUMMARY

This report has described briefly the design and performance of the two existing cold sources in high performance U.S. reactors. The constraints which led to the designs

have resulted in different compromises between performance and operation than have been achieved at other reactors and sources.

HFBR COLD NEUTRON FACILITY MEASURED FLUX GAIN

Courtesy of L. Passell, BNL Physics Dept

Existing Cold Sources at US Reactors

J. Michael Rowe

Questions/Answers/Comments

(S. Malik)

Question:

What is the maximum wavelength at which cold-neutron gain has been measured? How do these gain factors compare with that at 6 Å? Do calculations for your geometry support the observations?

Answer:

The gain for the NBSR source has been measured to approximately 15 Å. The observed gains saturate at approximately 3.5 - 4 times the best beam tube, or 5-6 (source full)/ (source empty). Calculations based on simple 2-D transport codes and multigroup diffusion codes are in good agreement with the observation. The calculations also reproduce the variation with H₂O content.

The gain at HFBR was measured out to approximately 15 Å. The results were consistent with those found for other hydrogen sources.

(C. West)

Question:

What is the physical temperature of the D₂O ice in the NBSR cold source?

Answer:

The average temperature is 35 to 40 K in the bulk of the ice.

(K. Gobrecht)

Question:

What is the mean effective temperature in the ice moderator? Which is the lowest temperature in it?

Answer:

For wavelengths greater than 3 Å, $T_{\text{eff}} \approx 65$ K. The lowest temperature is approximately 45-50 K.

(P. Egelstaff)

Question:

Can you tell us what mixtures of H and D have been tried at BNL and what results were found?

Answer:

Mixtures up to 0 to 25% D₂ in hydrogen were tried. The results were inconclusive but showed less than 10% increase in gain. We concluded that the results were not worth the trouble of mixing the gases for each charge of the moderator.

(P. Brewster)

Question:

Where are the supports for the vacuum-can plug and Bi shield? How much do they weigh? What is the design pressure of the hydrogen cold source chamber?

Answer:

The plug is supported along the bottom of the beam tube, and only the vacuum jacket and moderator chamber are cantilevered from the plug. The Bi tip is independently supported. The design working pressure is 5 atmospheres.

Cold Moderators for Pulsed Neutron Sources

John M. Carpenter
Argonne National Laboratory
Argonne, IL 60439

Abstract

This paper reviews cold moderators in pulsed neutron sources and provides details of the performance of different cold moderator materials and configurations. Analytical forms are presented which describe wavelength spectra and emission time distributions. Several types of cooling arrangements used in pulsed source moderators are described. Choices of materials are surveyed. I examine some of the radiation damage effects in cold moderators, including the phenomenon of "burping" in irradiated cold solid methane.

I. Introduction

As is the case in steady source (reactor) cold moderators, the main purpose of cryogenic moderators in pulsed sources is to produce long wavelength neutrons for neutron scattering and other applications. In pulsed sources there are additional strong motives for use of cold moderators. They provide short pulses at intermediate wavelengths where ambient temperature moderators exhibit a long tail associated with the Maxwellian spectrum. Even at very short wavelengths, the pulses can be made narrower in some cryogenic materials than in ambient temperature materials due to their significant thermal contraction and consequent higher proton densities at low temperature. Furthermore, some materials with attractive thermalization properties condense and can be used only at low temperatures.

In pulsed sources nuclear heating caused by gamma rays, fast neutrons and slow neutrons is substantially less than in reactor sources because the time average fluxes are a few orders of magnitude smaller, at least in present day pulsed sources. Furthermore pulsed source moderators are typically smaller than reactor cold sources; together with the lower heating rates this implies that

they require substantially smaller refrigerators than do reactor cold moderators. Radiation damage rates in pulsed sources are also lower than in reactors, which leaves more opportunity for the use of hydrocarbons as moderators. Because of the small volume of pulsed source moderators the inventory of combustible material and the related hazards are smaller than in the larger, D₂ systems in reactors.

Pulsed sources present a more detailed set of requirements and a greater range of requirements for different applications for cold moderators than do steady sources. But because of their lower time average power there are a greater range of prospects for meeting these requirements and for optimizing moderators for different applications than there are in reactors.

Figure 1 shows a typical arrangement of a target, moderator and reflector in a pulsed neutron source. To make the most of the available neutrons from the primary source, moderators are very close to the target. A reflector of Beryllium, for example, or other material surrounds the target and moderator to minimize leakage of neutrons from the moderator during slowing down, and to give neutrons which otherwise would have missed the moderator a chance to collide and slow down there. A layer of slow-neutron absorbing material (decoupler) surrounds the moderator and the neutron beam path to prevent long lived neutrons from the reflector from entering the moderator and broadening the pulse. In many cases a sheet of slow-neutron absorbing material (heterogeneous poisoning) is included below the viewed surface of pulsed moderators to control the width of the pulses.

Figure 1. A typical arrangement of a target, moderator and reflector in a pulsed spallation neutron source. Targets are around 20 cm in length and 10 cm in diameter; moderators dimensions are about 5x10x10 cm.

In the sections below, I review the installations of cold moderators in pulsed sources and present some analytical functions which describe the integrated intensities and the emission time distributions as functions of wavelength. Some arrangements used for cooling cold moderators in pulsed sources are described. Choices of moderating materials are surveyed. I examine some of

the radiation damage effects in cold moderator material, including the phenomenon of "burping" in cold solid methane.

II. Currently Operating Pulsed Sources and Cold Moderators

There are four pulsed spallation neutron sources and two pulsed reactors now operating for slow neutron research. Table I lists the pulsed spallation sources. All these have at least one cryogenic moderator. One of the early Argonne prototype spallation neutron sources, ZING-P' (operated from 1977 until 1980) had a liquid Hydrogen moderator. Two pulsed reactors IBR-30 and IBR-2 are operating at Dubna; plans are afoot to install a cold moderator in the 2 MW IBR-2.

TABLE I
Currently Operating Pulsed Spallation Neutron Sources

Source	Location	Target	Proton Current, μA	Proton Energy, MeV
IPNS	Argonne	235-enriched U	16.	450.
ISIS	Rutherford	238-U, Ta	110.	750.
KENS	KEK (Tsukuba)	238-U	10.	500.
LANSCE	Los Alamos	Tungsten	70.	800.

Until 1988, the IPNS target was of depleted Uranium. From time to time ISIS has used a Tantalum target. Originally the target of ZING-P' was of Tungsten; later the first depleted Uranium target was tested in ZING-P'.

Table II lists the cold sources now in operation or which operated in the past at pulsed spallation sources.

TABLE II
Cold Moderators at Pulsed Spallation Neutron Sources

Source	Designation, beams	Material	Temperature (K)	Dimensions (cm)	Poisoning
IPNS	"C" 1,2,2',3	L-H ₂	20.	10.x10.x7.6	none, grooved
IPNS	"F" 1-3,4-6	L-CH ₄	110.	10.x10.x5.	0.5 mm Cd @ 1.7 cm
IPNS	"H" 1,2,3	L-CH ₄	110.	10.x10.x5.	0.5 mm Cd @ 2.5 cm.
ISIS	N 4,5,6	L-H ₂	35.	11.x12.x8.	none
ISIS	N 1-3, S 6-9	L-CH ₄	100.	11.5x12.x4.5	none
KENS		S-CH ₄	25.	12.x15.x5.	none
LANSCE		L-H ₂	20.	12.x12.x7.	none
ZING-P'	"A"	L-H ₂	20.	10.x7.6x5.	none

The L-H₂ moderator at ISIS is actually supercritical Hydrogen at about 15 atm pressure.

The small dimensions of pulsed source moderators reflect the compromise of narrow pulse widths against time average intensity which is appropriate for traditional time-of-flight applications--the pulse widths at low neutron energies are principally determined by leakage. The small size of the moderators is matched to the small size of the primary neutron source, that is, the target. Furthermore, the typical dimension of the moderators is comparable to the mean free path of primary neutrons from the target and to the migration length of fast neutrons in the material.

Calculations of the performance of pulsed sources and moderators almost inescapably have to be performed with 3-D Monte Carlo codes with generalized geometry capability. This is because of the presence of strong absorbers, because the neutron spectrum varies greatly from region to region in the target-moderator-reflector assembly and because of the complexity and asymmetry that is typical of the spatial arrangements of moderators, beam paths and targets in pulsed sources. Further, it is necessary to recognize that the neutron population is driven by an external source; reactor criticality codes may need to be adapted for this application.

Accelerators, targets, moderators and neutron scattering instruments for spallation sources are the subjects of meetings of the International Collaboration on Advanced Neutron Sources (ICANS), held every other year. The most recently published are the proceedings of the 1988 meeting⁽¹⁾.

III. Materials for Pulsed Source Moderators

Protons are most efficient for slowing down fast neutrons because their mass is the same as that of the neutron and because their low energy neutron scattering cross section is larger than that of any other practical species. Except for considerations of finer detail addressed below, materials with high proton densities are preferred for pulsed source moderators. Table III lists a number of materials which are or may be useful as cryogenic moderators in pulsed sources.

TABLE III

Pulsed Source Moderator Materials

Material	Temperature, K	Proton Density, protons/Å ³	Melting and Boiling (1 atm) Temperatures, K
H ₂ O (for reference)	293	0.067	273, 373
(CH ₂) _n , 0.94 gm/cm ³ (ref)	293	0.081	-----
TiH ₂ (for reference)	293	0.095	-----
H ₂	20	0.042	14, 21
CH ₄	109	0.070	90, 110
CH ₄	10	0.079	90, 110
C ₂ H ₆	165	0.068	90, 184
C ₃ H ₈	228	0.064	83, 231
C ₁₂ H ₁₈ , Mellitine	293	0.047	439, 538
C ₉ H ₁₂ , Mesitylene	293	0.039	228, 438

Water (ice), polyethylene and metal hydrides in and of themselves are not effective cryogenic moderators materials because they have too few low frequency modes to provide efficiently for the final stages of thermalization, although their proton densities are quite high. Liquid Hydrogen is quite good in this regard, but the large (15 meV) rotational level spacing makes for large differences in the scattering between the low temperature para form and the normal ortho-para mixture; its low proton density leads to broad pulses of short wavelength neutrons. Liquid and solid methane are very attractive because of their good low-temperature thermalizing power, and have high proton densities as well. Ethane and propane are similarly attractive, with even lower rotational level spacings than methane, but have fewer rotational modes per proton than methane. Mellitine and mesitylene have freely rotating methyl groups but even fewer low frequency modes per proton and lower proton densities. They are attractive because they remain in condensed form at room temperature.

IV. Cooling Systems

The cooling systems of cryogenic moderators in pulsed sources are typically smaller than those in reactors, having a capacity of a few tens or hundreds of watts because of the smaller heat loads. Figure 2 illustrates three types, the recirculating liquid system, the recirculating liquid-gas system and the stationary system.

Figure 2a. Recirculating liquid system.

Figure 2b. Recirculating liquid-gas system.

Figure 2c. Stationary moderator system.

The "C" moderator in IPNS is a stationary system which can be filled with either Hydrogen or methane; cooling is provided by a 300 watt closed cycle Helium liquefier. The "F" and "H" moderators in IPNS are circulating liquid-gas systems; cooling is provided by evaporating liquid Nitrogen, through an intermediate loop of Helium gas. Both the liquid Hydrogen and the liquid methane moderators in ISIS are circulating liquid systems; cooling is provided by closed cycle Helium refrigerators. The liquid Hydrogen moderator in LANSCE is a circulating liquid system, also cooled by a closed cycle Helium refrigerator. The solid methane moderator in KENS is a stationary system, cooled by a Displex closed cycle Helium refrigerator. The liquid Hydrogen moderator in ZING-P' was a naturally circulating thermosyphon system.

The low thermal conductivity of hydrogenous solids at cryogenic temperatures requires that measures be taken to transport heat from within the moderators. Figure 3 illustrates two ways in which this has been accomplished.

Figure 3a. The KENS internal cooling system for solid methane.

Figure 3b. The IPNS internal cooling system for solid methane and liquid Hydrogen.

V. Radiation Damage

Aside from its eventual appearance as sensible heat, nuclear radiation, neutrons and gamma rays, produces chemical changes in cold moderator materials. In some cases this is harmless, but in other cases this leads to accumulation of troublesome products, and in solid methane it leads to temperature instabilities and damaging pressure excursions.

Hydrogen

Fast neutron and gamma ray interactions in Hydrogen H_2 and D_2 produce recoiling free protons and deuterons,

Recoiling protons can induce the same reaction as they slow down. In both the liquid and the gas the products harmlessly and rapidly recombine due to the fast diffusion of the ions

I do not know how rapidly this recombination takes place in the low temperature solid.

Hydrocarbons (e.g. CH₄)

In methane and other hydrocarbons the principal initiating radiolysis reaction is (for example in methane)

which is rapidly followed by recombination according to

from which H₂ accumulates and also according to

which takes place rapidly and produces more CH₃, and

In liquid (and gas) the recombination according to (e) takes place quickly due to the rapid diffusion of methyl radicals. In the solid the diffusion rate can be very slow, leading to long-term storage of chemical energy which can be released upon externally induced warming or externally controlled changes in the coupling of the cooled material to the coolant, or released spontaneously after building up to critical concentrations. This is the origin of the "burping" phenomenon which is discussed further below.

Recombination according to (e) is not the only possible result. It has been known for a long time that in gaseous methane a single initiating event can lead to recombination into quite heavy hydrocarbons, up to about 20 carbons long, albeit with lower probability than (e). We have observed this in liquid methane, where the heavier products build up more-or-less in proportion to the time or accumulated dose. This is evidence for the direct formation of heavier hydrocarbons as opposed to a sequential buildup which would lead to t^n behavior of the concentration of, say, C_nH_x. Although the intermediate weight hydrocarbons are volatile and soluble in methane and have thermophysical properties rather like methane (see Table II), the heavy hydrocarbons can rapidly exceed solubility limits and collect in pipes and elsewhere to obstruct flows and inhibit heat transfer. Table IV shows the results of gas chromatographic analysis of the contents of the circulating loop of the IPNS "F" moderator system, after one week's operation starting with a

fresh charge of pure methane. The accelerator delivered an average current of 15 μ A to the Booster Target; the H₂ separator was not in operation.

TABLE IV.

Molar Concentrations of Compounds in Gas from the Circulating Side of the IPNS "F" Moderator After One Week of Operation at 15 μ A with the Booster Target

Material	Concentration
H ₂	22.6 %
CH ₄	75.2 %
C ₂ H ₄	< 0.16 %
C ₂ H ₆	1.50 %
C ₃ H ₈	0.39 %
C ₄ H ₁₀	< 0.07 %

The distribution of radiolysis products seems to be different in solid methane than it is in liquid methane, based on analyses of the volatile products of irradiation in liquid and solid moderators in IPNS.

H₂ can accumulate beyond the solubility limits both in the liquid and in the solid material. In circulating liquid methane systems the Hydrogen-rich vapor phase, even at the level of a few mole percent H₂, can accumulate to exclude a significant fraction of the liquid phase, due to the low density of the vapor. In solid methane excess H₂ collects but has a low vapor pressure at temperatures below about 20 K. When the temperature rises, Hydrogen trapped in the solid exerts its higher vapor pressure on the entire solid and its container. If the container is insufficiently compliant and the compressibility of the solid is insufficient to accommodate the expansion of trapped Hydrogen, the resulting stresses can cause the container to fail. This has happened in IPNS, once in a single event which led to very high pressures, and in other instances where numerous stress cycles led to fatigue failures.

Water

In water (H₂O or D₂O) radiolysis leads to formation of H₂ (D₂), OH radicals, O₂, O₃ and possibly H₂O₂ as stable or metastable products. At low temperatures energy can be stored in the form of these reactive species as in cold solid methane. Even though the only eventual stable product of recombination is again water (unless some product is removed), the potential for release of stored energy and for pressure increases due to expansion of trapped gases is similar to that in solid methane.

Degradation of Performance

In addition to causing operational problems, radiation damage effects of various kinds accumulate to degrade the neutronic performance of most materials, largely because of the loss of bound protons and partly because of the formation of Hydrogen and heavy hydrocarbons. This is most important in the case of solid moderators, such as polyethylene and solid methane⁽²⁾.

VI. Wavelength Spectra

Of the two principal measures of the performance of pulsed source cold moderators, spectra and pulse shapes, the wavelength spectra are easiest to measure. Figure 4 shows the usual arrangement.

Figure 4. Arrangement for measuring the wavelength spectrum of a pulsed source moderator.

The time average counting rate in the detector $C(t)$ per unit time-of-flight t is

$$C(t) = A\eta(\lambda)\phi(\lambda)(h/mL) + B \quad (1)$$

where B is the background (primarily due to delayed neutrons from fissionable targets), A is the area of the beam incident on the detector, $\eta(\lambda)$ is the detector efficiency for neutrons of wavelength λ , $\phi(\lambda)$ is the time average flux per unit wavelength at the location of the detector, $(h/m) = 3955.4 \text{ \AA-m/sec}$ is the ratio of Planck's constant to the neutron mass, L is the distance from the moderator surface to the mean position of the detector and (ignoring wavelength dependent emission time delays and shifts of the mean detection position)

$$t = (h/mL)\lambda. \quad (2)$$

In this context it is conventional to express fluxes as functions of the energy E ,

$$E = (\hbar^2/2m)/\lambda^2 \quad (3)$$

where in practical units $(\hbar^2/2m) = 81.787 \text{ meV-\AA}^2$. The flux per unit energy $\phi(E)$ is related to the flux per unit wavelength

$$\phi(E) = (\lambda/2E)\phi(\lambda) \quad (4)$$

The flux is related to the "beam current" of the moderator $i(E)$ (in analogy with light sources, $i(E)$ is a luminous intensity, equal to the total number of neutrons per unit time per unit energy, per steradian in the direction of the beam)

$$\phi(E) = i(E)/L^2 \quad (5)$$

which is an intrinsic property of the moderator. When the detector is a low efficiency "1/v" detector,

$$\eta(\lambda) = K\lambda, \quad (6)$$

where K is a constant, and the counting rate is proportional to $E\phi(E)$

$$C(t) = 2AK(h/mL)E\phi(E) \propto E\phi(E). \quad (7)$$

Ignoring corrections due to the attenuation of neutrons by air or structural material in the beam (or assuming that these corrections have been made) the flux can usually be accurately represented

$$\phi(E) = \phi_{MB}(E) + \phi_{SD}(E). \quad (8)$$

except in the important case of liquid hydrogen moderators. $\phi_{MB}(E)$ is a Maxwellian function

$$\phi_{MB}(E) = (E/E_T^2)e^{-E/E_T} \phi_{Th}, \quad (9)$$

with mean energy (the "thermal energy")

$$E_T = k_B T_{eff}. \quad (10)$$

$k_B = 0.086165$ meV/K is Boltzmann's constant and T_{eff} is the "effective temperature" of the distribution, which is always greater than the physical temperature of the moderator. $\phi_{MB}(E)$ is normalized

$$\int_0^\infty \phi_{MB}(E)dE = \phi_{Th}, \quad (11)$$

where ϕ_{Th} is the time average "thermal" neutron flux. In the case of small moderators, especially liquid Hydrogen moderators, the low energy flux distribution is not of Maxwellian form. (It is beyond the scope of this paper to discuss the origin of this phenomenon and some of the general features of the time and wavelength distributions which are the basis of the present discussion. Underlying is the extensive theory of time-dependent neutron thermalization. The reader interested in further exploration may profitably consult, for example, the excellent treatise of Williams⁽³⁾ or the illuminating discourse by Parks, Nelkin, Beyster and Wikner⁽⁴⁾.)

$\phi_{SD}(E)$ is a "slowing-down" function

$$\phi_{SD}(E) = (1/E)(E/E_{Ref})^\alpha \Delta_1(E) \Delta_2(E) \phi_{epi}, \quad (12)$$

where ϕ_{epi} is the time average epithermal neutron flux, a constant given by

$$\Delta_1(E_{\text{Ref}}) \Delta_2(E_{\text{Ref}}) \phi_{\text{epi}} = E_{\text{Ref}} \phi_{\text{SD}}(E_{\text{Ref}}) . \quad (13)$$

E_{Ref} is an arbitrarily chosen reference energy, conventionally 1. eV, and α is the "leakage exponent, a positive number usually less than 0.1.

$\Delta_1(E)$ is the "joining function". Several empirical forms have been used to represent $\Delta_1(E)$; we use a generalization of Westcott's joining function,

$$\Delta_1(E) = \frac{1}{1 + (E_{\text{co}}/E)^s} , \quad (14)$$

where s is the "cutoff exponent" and E_{co} is the "cutoff energy"; usually around $E_{\text{co}} \approx 5.0 E_T$. To avoid an infrared catastrophe, $s > 2 - \alpha$, but usually $s \approx 5.0$.

In methane it is necessary to account for a prominent bump in the spectrum presumably associated with the high frequency vibrational modes of the molecule. We have characterized this bump entirely empirically in the form of a stretched Gaussian function

$$\Delta_2(E) = 1 + C e^{-(E^p - E_B^p)^2 / 2\sigma^2} \quad (15)$$

where E_B is the energy at which the bump appears, p is the stretching exponent which we find is around $-2/3$ but do not refine in least squares analysis, and σ is the width parameter. The coefficient C represents the amplitude of the bump.

Usually, $2. < \phi_{\text{TH}}/\phi_{\text{epi}} < 5.$, a much smaller ratio than is characteristic of steady reactor sources, therefore pulsed sources provide useful fluxes of neutrons at wavelengths far shorter than the peak of the Maxwellian. For most pulsed sources, the time-average epithermal neutron flux is around $\phi_{\text{epi}} \approx (3 \times 10^{-4} \text{ neutrons/ster/source neutron}) \times S/L^2$ where S is the time average global leakage rate of neutrons from the primary source.

Nonlinear least-squares fitting algorithms usually converge rapidly and robustly to a well-fitting solution, given a sufficient range of time-of-flight data.

Figure 5 shows spectra for three different moderators. Each curve represents a function fitted to spectra corrected for attenuation in air and Aluminum, then recalculated with the corrections reapplied. Delayed neutron backgrounds are not shown, but represent about 2.8 % (with the Booster Target of IPNS, 0.44 % with the depleted Uranium target) of the total number, spread uniformly across the $1/30^{\text{th}}$ second long time interval between pulses in IPNS. The relative magnitude of this background thus depends on the distance from the moderator to the detector in which the spectra are measured, but the fraction of delayed neutrons in the background is invariant.

Figure 5. Comparison of flux spectra for 350 K polyethylene, 105 K liquid methane and 20 K grooved, solid methane.

Three spectra are shown, one for ambient temperature (about 350 K) polyethylene poisoned with .5 mm Cd 25 mm below the viewed surface, one for a 105 K liquid methane moderator similarly poisoned 17 mm below the surface and one for an unpoisoned, grooved, 20 K solid methane moderator. Comparing the polyethylene and liquid methane spectra in the range of the Maxwellian peak, two effects are visible: the peak of the Maxwellian is shifted in wavelength as expected according to the square root of the temperature ratio; the more severe poisoning of the liquid methane moderator leads to a significant loss of the integrated intensity in the Maxwellian, even so the flux of long wavelength neutrons from the liquid methane is about 3 times higher. Comparing the solid methane with the polyethylene reveals two effects: the 20 K moderator shifts the Maxwellian to still longer wavelengths, and the grooved, unpoisoned moderator produces a larger Maxwellian flux relative to the epithermal flux, with the result that in the limit of long wavelengths, neutron flux from the grooved, cold solid methane is more than 300 times greater than that from the room temperature polyethylene.

The discontinuity at $4.67\text{\AA}$ arises due to the [111] Bragg edge in the scattering cross section of Aluminum and is one of several such features caused by Aluminum windows and other structure in the beam; these serve as markers of the wavelength scale.

Reference (5) contains a survey of the effects of poisoning, cooling and materials choices upon the spectra and pulse shapes.

VII. Pulse Shapes (Emission Time Distributions)

For conventional time-of-flight applications, the width -- indeed the detailed shape -- of the pulse as a function of time is a defining factor in the resolution of instruments. In principle, the shape of the pulse of primary neutrons from the source broadens the pulse from a moderator, but since in all the operating pulsed spallation sources the primary source pulse width is quite short, this broadening is ignored in the present discussion. The pulse shapes are then entirely determined by the features of the moderators, and the pulse shape is a strong function of the wavelength. Reflectors surrounding the moderators also affect the pulse shapes, but effective decoupling reduces these effects to insignificance for neutrons with wavelengths in the range of interest and they are ignored here. It is useful to discuss pulse shapes in two regions, the short wavelength, epithermal range, and the longer-wavelength, thermal range.

Measurements of the Pulse Shape

The pulse of neutrons emitted from the moderator is conveniently characterized by the time and wavelength distribution at the viewed surface. Measurements can be made remotely, using a "time-focussed" single crystal diffraction method^(6,7), shown in Figure 6. The monochromating crystal is cut perpendicular to the [220] planes; the [111] planes are the reflecting planes.

Figure 6. Time Focussed Crystal Spectrometer arrangement for measuring the emission time distribution as a function of wavelength

With such an arrangement, using a thin crystal and a thin detector and having the proper relationships between the ratio of flight paths, moderator viewing angle, crystal cut and detector orientation angles and Bragg angle, the emission time distribution can be measured with negligible time broadening, even when viewing large areas of moderator, crystal and detector. All allowed orders of the aligned reflection are seen, which enables separate determinations of the pulse shape for many wavelengths in a single setup. Cooling the crystal to low temperature enhances the intensity for short wavelengths by reducing the Debye-Waller exponent for high order reflections.

Pulse Shapes for Short Wavelengths.

For short wavelength neutrons, the shape of the pulses is closely approximated by the function describing slowing down in infinite hydrogenous moderators,

$$i(t, \lambda) = (a(\lambda)t)^2 e^{-a(\lambda)t} \bar{i}(\lambda)/2a(\lambda)f, \quad (16)$$

where $\bar{i}(\lambda)$ is the time average beam current per unit wavelength, f is the source pulsing frequency and

$$a(\lambda) = v\Sigma_s(\lambda) \quad (17)$$

in which v is the neutron speed and $\Sigma_s(\lambda)$ is the macroscopic proton scattering cross section. The pulse FWHM is $3.394/a(\lambda)$ and the pulse standard deviation is $\sqrt{3}/a(\lambda)$, and is therefore inversely proportional to the proton density. For short wavelengths, the cross section is constant, so the pulse width is proportional to the wavelength.

For longer-wavelength neutrons, in the range of the Maxwellian, the pulse shape is dominated by the exponential decay of the fundamental eigenfunction of the neutron distribution in the moderator. The pulse has a sharp rising edge which reflects partly the rise of the slowing down function, and partly the convolution of that function with an abruptly turned-on falling exponential. Susumu Ikeda ⁽⁷⁾ found that the function represented schematically in Figure 7 fits room temperature polyethylene pulse shapes very well.

Figure 7. Ikeda's function.

The asterisk denotes convolution. $\delta(t)$ is the delta function, β is a constant, $R(\lambda)$ is the wavelength-dependent fraction of the intensity in the exponentially-decaying "storage" term and $(1 - R(\lambda))$ is the fraction in the slowing-down term. This function does not fit the pulse shapes for liquid methane as accurately as it does for those of polyethylene--a third term seems to be required in this form. The form fitted to data for unpoisoned liquid methane by Taylor and Robinson ⁽⁸⁾, shown in Figure 8,

Figure 8. The function of Taylor and Robinson.

fits the data reasonably well. Here, α , t_0 and σ as well as R depend on the wavelength; β is a constant smaller than α . More work needs to be done in characterizing these distributions. Figure 9 shows the shapes of pulses from a poisoned liquid methane moderator and from a poisoned ambient temperature polyethylene moderator, for 2.843 Å and 1.137 Å neutrons. The polyethylene had degraded after lengthy irradiation, and the liquid methane was somewhat less dense than theoretical because of frothing which arose because of the accumulation of Hydrogen vapor in the container.

Figure 9. Pulse shapes at two wavelengths for an ambient temperature polyethylene moderator poisoned with .5 mm Cd, 22 mm beneath the viewed surface, and for a liquid methane moderator, poisoned 17 mm beneath the viewed surface.

The poisoning, which is at different depths in the two moderators, mainly affects the length of the decaying tail on the pulses. The pulse width and the integrated intensity of the pulse are adjustable by changing the poison depth. The pulse of 1.137 Å neutrons from the liquid methane is a sample from the epithermal distribution; it does not exhibit much of the slowly decaying exponential, which still influences the pulse of 1.137 Å neutrons from the ambient temperature moderator. The remarkable feature of these distributions is the sharpness of the leading edge of the pulse, which leads to a gain in information in terms of spectrometer resolution. Neutrons thermalize faster in methane than in polyethylene, evidently because of the presence in methane of the rich distribution of low energy modes of excitation. This produces a much sharper leading edge on the pulses of low energy neutrons from methane than from polyethylene. Figure 10 shows the full width at half maximum of the pulses from the same two moderators, as functions of wavelength. The FWHM is a crude measure of the pulse shapes and does not reveal their details, in particular the sharp leading edges, but the figure shows the general trend of the pulse widths.

Figure 10. The Full Width at Half Maximum of pulses from a poisoned ambient temperature polyethylene moderator and from a poisoned liquid methane moderator, vs wavelength. The curves are physically-motivated rational polynomials fitted to the data.

At the shortest wavelengths, the pulse widths are proportional to the wavelength. At longer wavelengths, the pulse widths rise, reflecting the presence of the exponentially-decaying fundamental eigenfunction. At longest wavelengths, the pulse widths level off since the decay time of the fundamental mode is independent of wavelength. In the cold moderator, the desirable proportional region extends to longer wavelengths than in the ambient temperature moderator because the Maxwellian spectrum is confined to longer wavelengths. Best resolution in time-of-flight, as measured by FWHM, occurs where FWHM/λ is smallest; this happens at the longest wavelengths.

VIII. Thermalization Properties of Cold Moderator Materials

Eligible materials for cold moderators must exhibit a rich spectrum of low frequency modes which can absorb small quanta of energy, to enable neutrons to equilibrate at low temperature. All materials have low frequency acoustic wave modes or their equivalent, but only the low frequency tail of the Debye spectrum (in solids) or a small component of diffusive scattering (in liquids) is active at low temperatures and at low neutron energies. The best materials for pulsed source applications, in which the moderator is small, have additional low frequency molecular rotational modes, as for example in H_2 and CH_4 . Figure 11 shows the rotational level diagrams for H_2 and CH_4 .

Figure 11. Rotational energy level diagram for hydrogen and methane.

Para Hydrogen, with even angular momentum quantum numbers has the lowest energy and at low temperatures is the predominant phase. However ortho Hydrogen is metastable and in the absence of catalysts requires many hours to convert to para Hydrogen. Neutrons induce the transition from para to ortho and can lose the roughly 15 meV energy difference between the $J = 0$ and the $J = 1$ levels; the minimum energy loss in scattering from ortho Hydrogen is 30 meV. Thus neutrons with energies below 15 meV energy cannot excite rotational transitions.

The total neutron scattering cross section is dramatically different for the two species. Figure 12 shows the total scattering cross sections of normal (ortho:para = 3:1) and para Hydrogen as a function of neutron energy.

Figure 12. The total scattering cross sections of normal and para Hydrogen.

In ortho (and normal) H₂ the scattering at low energies is elastic insofar as rotational excitations are concerned; only center-of-mass motions can absorb energy in scattering. In small moderators the inferior low energy inelastic scattering properties of para H₂ are compensated somewhat by the low total cross section, which allows low energy neutrons to stream out once they have reached low energies. Figure 13 shows the inelastic scattering function of 9 K solid methane.

Figure 13. The scattering function of solid methane at 9 K, measured at scattering angle 90° scattering angle and for final energy 3.6 meV. The peaks at 8, 16 and 24 cm⁻¹ (1., 2., 3. meV) are rotational transitions of the nearly-free methane molecule.

The rotational peaks at 1, 2, 3 meV are responsible for the excellent thermalization properties of solid and liquid methane.

IX. The "Burping" Phenomenon

When cold solid methane is irradiated with high energy neutrons, H_2 and CH_3 accumulate as discussed in section III above. Free protons or monatomic Hydrogen rapidly combines with CH_4 to form H_2 and CH_3 . The methyl radicals diffuse (the diffusion is probably a virtual diffusion, wherein the CH_3 identity moves by proton hopping) and recombine only slowly at low temperatures. Then they can accumulate to such densities that upon recombination their heat of recombination raises the temperature of the material significantly, increasing the diffusion rate and triggering further recombination. This happens spontaneously if the rate of production of the methyl radicals ("defects") is large enough, and can also be induced by externally controlled warming or by changing the cooling conditions. The process has been called "burping"⁽⁹⁾. (Identifying methyl groups rather than monatomic Hydrogens as the energy storing defects represents a departure from the discussion in reference (9); this departure is based on more accurate chemical information than I was aware of at the time of writing that paper.) The resulting temperature rise can be sufficient that the vapor pressure of the accompanying trapped Hydrogen reaches several atmospheres, and endangers the container. Figure 14 shows the temperature measured during an induced "burp" in the cold solid methane moderator, which had been irradiated in IPNS for about one day with about $7. \times 10^{18}$ protons on the depleted Uranium target. The energy released, computed from the temperature rise and the heat capacity of the methane and the container, represents about 1.1 joules per gram.

Figure 14. The temperature at the center of the IPNS "C" moderator as a function of time after an externally induced "burp".

A lumped parameter description of the system provides insight into its behavior;

$$\frac{dN}{dt} = R(t) - K(T)N^2 \quad (18)$$

$$MC(T) \frac{dT}{dt} = P(t) + EK(T)N^2 - H(T, t)(T - T_{cool}(t)), \quad (19)$$

where $N(t)$ is the total number of "defects" (CH_3 's), $R(t)$ is the rate of production of defects in the system, $K(T)$ is a recombination rate coefficient, $T(t)$ is the temperature, $C(T)$ is the heat capacity of the system, $P(t)$ is the total power input to the system, E is the energy released per recombination event, $H(T, t)$ is the coefficient for heat transfer between the system and the coolant and $T_{cool}(t)$ is the temperature of the coolant. $C(T)$ and $H(T, t)$ are strong (and unknown) functions of the temperature. (18) assumes binary recombination of defects and (19) assumes Newton's law of cooling. $K(T)$ is assumed to have the Arrhenius form,

$$K(T) = K_0 \exp(-\Delta E/k_B T), \quad (20)$$

where ΔE is an activation energy and k_B is Boltzmann's constant and K_0 is a constant or at worst a mild function of T . $T_{cool}(t)$ and $H(T, t)$ are externally controllable variables. The equations are highly nonlinear, not only because of the binary recombination law and the temperature dependence of the coefficients, but most significantly because of the Arrhenius law dependence of the recombination rate upon the temperature. Of course the system could be more accurately described as a distributed system, but such a description is beyond our current capabilities which are already limited by the lack of detailed information.

Numerical solution of the "burp equations", (18) and (19), reveals that there are two regimes of behavior. When the temperature is high, the defect production rate low, the heat capacity or the heat transfer coefficient large, the system monotonically approaches a state of steady equilibrium. Otherwise, the system exhibits nonlinear, bounded oscillatory behavior which is the "burping" that is observed. Figure (15) shows the result of Runge-Kutta integration (to handle the widely-changing derivatives) of the burp equations for conditions that lead to oscillation; the coefficients are assumed to be independent of temperature, except that the actual heat capacity of the system, including the 20.4 K transition in CH_4 , is correctly included. We find that the activation temperature $T_E = \Delta E/k_B$ must be around 150 K.

Figure 15. Runga-Kutta integration of the burp equations.

The coolant temperature decreases linearly in the calculation, beginning at a high temperature so that the system does not oscillate. Eventually, the moderator temperature becomes low enough that the system oscillates, beginning with a small ripple just before the large excursion at 110,000 seconds. The frequency of oscillations decreases and the energy released in each excursion increases as the temperature becomes lower. The lumped parameter model seems to be incapable of accurately describing the details of the excursions.

Burping behavior has also been observed in the KENS cold methane moderator, but only since the installation of the depleted Uranium target which increased the radiation damage rate. Presumably that increase pushed the KENS system across the threshold for oscillation. Burping has been observed from the outset of operation of the IPNS cold solid methane moderator. In anticipation of greater burping difficulties upon the installation of the Enriched Uranium Booster Target, we are temporarily using liquid Hydrogen. We believe that it will be possible to live with the burping by following some annealing schedule in which the stored energy is periodically released and, perhaps with lower frequency, the trapped Hydrogen is removed. The KENS moderator is now operated with such an annealing program.

X. Conclusions

Cold moderators using liquid Hydrogen, liquid methane and solid methane are in fruitful use in all the operating pulsed spallation neutron sources. They have been optimized for different applications, but are yet in a stage of rapid development. Problems of clogging and voiding due to the accumulation of radiation damage products remain to be solved even at the present levels of power density and radiation damage density, as do the problems of controlling and accommodating the effects of burping. Methods for characterizing their performance have been reasonably well worked out, and the performance of the existing cold moderators is fairly well understood. Further developments can be expected involving the use of other moderating media and construction material and other modes of operation. Calculations and tests of neutronic performance should be performed to improve the optimization of geometries and to assess new

choices of materials. Further work is called for to improve the operational reliability of existing cold sources, and to provide moderators for sources of higher power in the future.

XI. Acknowledgements

This work was performed under the auspices of the U. S. Department of Energy, Division of Materials Sciences, under Contract W-31-109-Eng-38.

XII. References

1. "Advanced Neutron Sources 1988", (ICANS X), edited by D. K. Hyer, Institute of Physics Conference Series Number 97, Institute of Physics, Bristol and New York, 1989.
2. J. M. Carpenter, S. S. Cudrnak and C. M. DeCusatis, "Deterioration of Performance Of Neutron Moderators Under Intense Irradiation", Proceeding of the 9th Meeting of the International Collaboration on Advanced Neutron Sources, Villigen, Switzerland, September, 1986, (ICANS IX), Public Affairs Office, Swiss Institute for Nuclear Research, Villigen (July, 1987). ISBN-3-907998-01-4.
3. M. M. R. Williams, "The Slowing Down and Thermalization of Neutrons", North-Holland Publishers, Amsterdam (1966).
4. D. E. Parks, M. S. Nelkin, J. R. Beyster and N. F. Wikner, "Slow Neutron Scattering and Thermalization", W. A. Benjamin, Inc., New York (1970)
5. "Neutron Sources", J. M. Carpenter and W. B. Yelon, in "Methods of Experimental Physics", editors-in-chief R. Celotta and J. Levine, Volume 23A, "Neutron Scattering", edited by K. Sköld and D. L. Price, Academic Press, Orlando, 1986. Chapter 2.
6. K. F. Graham and J. M. Carpenter, "Pulsed Moderator Studies Using a Time Focussed Crystal Spectrometer", Nuclear Instruments and Methods **85**, 163 (1970).
7. S. Ikeda and J. M. Carpenter, "Wide Energy Range, High-Resolution Measurements of Neutron Pulse Shapes of Polyethylene Moderators", Nuclear Instruments and Methods in Physics Research **A239**, 536 (1985).
8. J. M. Carpenter, A. D. Taylor, R. A. Robinson and D. J. Picton, "Measurement and Fitting of Spectrum and Pulse Shapes of a Liquid Methane Moderator at IPNS", Nuclear Instruments and Methods in Physics Research **A234**, 542 (1985).
9. J. M. Carpenter, "Thermally Activated Release of Stored Chemical Energy in Cryogenic Media", Nature Vol. **330**, 358 (1987).

Cold Moderators for Pulsed Neutron Sources

Jack M. Carpenter

Questions/Answers/Comments

(P. Egelstaff)

Question:

Isn't the burp process the same as the Wigner energy release familiar to operators of nuclear reactors? Can you learn anything from their experience?

Answer:

In a very broad sense, the processes are similar. However, in graphite, energy is stored in the form of lattice defects, while in solid methane energy seems to be stored in the form of reactive methyl radicals. The major difference is that in the methane case the rate of energy release is proportional to the square of the stored energy (methyl radical) density; in graphite the energy release rate is probably a more complicated function of the stored energy density. Both processes are thermally activated, but the difference in the density dependence of the energy release rates leads to differences in the mathematical descriptions of the two phenomena and in the details of behavior of the two systems.

In a practical sense, the management of the stored energy may come down to similar procedures, whereby the stored energy is released in a controllable manner by periodic annealing. Hydrogen produced simultaneously with the methyl radicals by radiolysis exacerbates the problem in solid methane because even modest temperature increases lead to large increases in the pressure of trapped hydrogen.

(R. Pynn)

Question:

You mentioned the problem of production of hydrogen in liquid methane moderators. How is this overcome at ISIS?

Answer:

I think that the H_2 is exhausted from some high point in the system, say from a surge tank. Some CH_4 must be lost with it. It will be best to inquire directly of the ISIS engineers.

Session II

NEUTRONICS CALCULATION AND MEASUREMENTS

Chairman

J. Eric Lynn

Neutron Slowing Down and Thermalization

V. F. Sears

Atomic Energy of Canada Limited
Chalk River, Ontario, Canada K0J 1J0

ABSTRACT

We present a concise introduction to the theory of cold-source neutronics. The basic quantities and concepts are established within the framework of neutron transport theory, and simple analytical models are used to explore some of the essential physics. Detailed numerical results are presented for a variety of model scattering kernels.

I. INTRODUCTION

The calculation of the thermalization and diffusion of neutrons in a cold source using accurate scattering kernels and realistic moderator geometries is a specialized problem in reactor physics that is discussed in detail by other speakers at this workshop. The main purpose of this paper is to introduce the basic quantities and concepts, and to highlight some of the underlying physics with the help of simplified models. In particular, we discuss the behavior of a cold source in two limiting cases. First, we consider a large well-thermalized source, in which the neutrons are simply cooled at constant density from the ambient temperature of the reactor to, for example, liquid-hydrogen temperature. Second, we discuss a small undermoderated source, where the incident neutrons are only scattered once before leaving it. These limits can be treated analytically, and we demonstrate that, in both cases, significant flux gains are obtained in the cold-neutron region. The behavior of a real cold source will, of course, fall between these two limiting cases.

We begin in Sec. II with a brief review of neutron transport theory, which provides the framework for all discussions of the slowing down and thermalization of neutrons in a cold source or, indeed, in any moderator.

II. NEUTRON TRANSPORT THEORY

Phase-Space Distribution Function

The fundamental quantity in neutron transport theory^[1,2] is the phase-space distribution function $f(\mathbf{r}, \mathbf{v}, t)$, which is defined such that $f(\mathbf{r}, \mathbf{v}, t) d\mathbf{r} d\mathbf{v}$ is the average number of neutrons in the volume element $d\mathbf{r}$ with velocity in $d\mathbf{v}$ at time t . Once we know this quantity, we can calculate all other quantities of interest. These include, for example, the neutron number density,

$$n(\mathbf{r}, t) = \int f(\mathbf{r}, \mathbf{v}, t) d\mathbf{v} , \quad (1)$$

the neutron current density, or vector flux,

$$\mathbf{J}(\mathbf{r}, t) = \int \mathbf{v} f(\mathbf{r}, \mathbf{v}, t) d\mathbf{v} , \quad (2)$$

and the scalar flux,

$$\Phi(\mathbf{r}, t) = \int v f(\mathbf{r}, \mathbf{v}, t) d\mathbf{v} , \quad (3)$$

in which $v = |\mathbf{v}|$ is the neutron speed.

Transport Equation

Whenever a neutron collides with a nucleus in a moderator, the neutron is either scattered or absorbed. In neutron transport theory it is assumed that, between collisions, the neutron moves as a classical particle with a constant velocity $\mathbf{v}$. This leads to a transport equation of the form

$$\left\{ \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right\} f(\mathbf{r}, \mathbf{v}, t) = \int \left[\rho v_0 \sigma_s(\mathbf{v}_0, \mathbf{v}) f(\mathbf{r}, \mathbf{v}_0, t) - \rho v \sigma_s(\mathbf{v}, \mathbf{v}_0) f(\mathbf{r}, \mathbf{v}, t) \right] d\mathbf{v}_0 - \rho v \sigma_a(\mathbf{v}) f(\mathbf{r}, \mathbf{v}, t) . \quad (4)$$

Here, ρ is the number of atoms per unit volume in the moderator, $\sigma_s(\mathbf{v}_0, \mathbf{v})$ is the scattering kernel (essentially, the double differential scattering cross section), and $\sigma_a(\mathbf{v})$ is the absorption cross

section. The transport equation (4) is a linear equation because it ignores the possibility of neutron-neutron collisions. This assumption is justified by the fact that the neutron number density n is always many orders of magnitude smaller than the atomic number density ρ .

For the materials used as neutron moderators, the absorption cross section is always much smaller than the scattering cross section and obeys the familiar $1/v$ law^[3]:

$$\sigma_a(v) = \frac{\text{const}}{v} . \quad (5)$$

Thus, the only unknown coefficient in the transport equation (4) is the scattering kernel. Neutronics calculations for a cold source therefore divide naturally into two distinct parts: (i) the determination of a suitable model for the scattering kernel $\sigma_s(v_0, v)$ and, (ii) the solution of the transport equation, under appropriate boundary conditions and initial conditions, to determine the phase-space distribution function $f(\mathbf{r}, \mathbf{v}, t)$.

Scattering Kernel

A conventional neutron inelastic scattering experiment is described by the double differential scattering cross section $d^2\sigma$, defined as the average number of incident neutrons with velocity $\mathbf{v}_0$ scattered into the volume element $d\mathbf{v}$ per atom, per unit time, per unit incident flux. The scattering kernel is then defined such that

$$d^2\sigma = \sigma_s(v_0, v) d\mathbf{v} . \quad (6)$$

If (θ, ϕ) are the polar coordinates of $\mathbf{v}$ with respect to $\mathbf{v}_0$ as polar axis, then

$$d\mathbf{v} = v^2 dv \sin\theta d\theta d\phi = \frac{v}{m} d\Omega dE , \quad (7)$$

where m is the neutron mass, $d\Omega = \sin\theta d\theta d\phi$ is the element of solid angle, and $E = (1/2)mv^2$ is the scattered-neutron energy. Hence,

$$\frac{d^2\sigma}{d\Omega dE} = \frac{v}{m} \sigma_s(v_0, v) . \quad (8)$$

On the other hand, a quantum-mechanical calculation of the double differential scattering cross section, within the usual Born approximation, shows that^[4]

$$\frac{d^2\sigma}{d\Omega dE} = \left(\frac{\sigma_s}{4\pi\hbar} \right) \frac{v}{v_0} S(\mathbf{q}, \omega) , \quad (9)$$

where σ_s is the bound scattering cross section per atom, which characterizes the neutron-nucleus interaction, and $S(\mathbf{q}, \omega)$ is the dynamic structure factor, or "scattering law", which characterizes the structure and dynamics of the scattering system in the absence of the interaction with the neutron. Here, $\mathbf{q}$ and ω are the momentum and energy, in units of $\hbar$, transferred from the neutron to the system in the collision:

$$\hbar\mathbf{q} = m\mathbf{v}_0 - m\mathbf{v} , \quad \hbar\omega = E_0 - E . \quad (10)$$

Comparing (8) and (9), we see that the scattering kernel is proportional to the dynamic structure factor:

$$\sigma_s(\mathbf{v}_0, \mathbf{v}) = \frac{m\sigma_s}{4\pi\hbar v_0} S(\mathbf{q}, \omega) . \quad (11)$$

Total Cross Section and Mean Free Path

The total scattering cross section is given by

$$\sigma_s(\mathbf{v}_0) = \int \sigma_s(\mathbf{v}_0, \mathbf{v}) d\mathbf{v} . \quad (12)$$

For an isotropic system, we can regard this quantity as a function of E_0 , in which case it follows from (7) that

$$\sigma_s(E_0) = \int_0^\infty \sigma_s(E_0, E) dE , \quad (13)$$

where

$$\sigma_s(E_0, E) = \frac{v}{m} \int_{4\pi} \sigma_s(\mathbf{v}_0, \mathbf{v}) d\Omega . \quad (14)$$

The total collision cross section is given by

$$\sigma_t(\mathbf{v}_0) = \sigma_s(\mathbf{v}_0) + \sigma_a(\mathbf{v}_0) . \quad (15)$$

Using (12) and (15), we see that the neutron transport equation (4) can then be expressed in the alternative form

$$\left\{ \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla + \rho v \sigma_t(\mathbf{v}) \right\} f(\mathbf{r}, \mathbf{v}, t) = \int \rho v_0 \sigma_s(\mathbf{v}_0, \mathbf{v}) f(\mathbf{r}, \mathbf{v}_0, t) d\mathbf{v}_0 . \quad (16)$$

The coefficient $\rho v \sigma_t(\mathbf{v})$ can be interpreted as the inverse mean time between collisions for a neutron of velocity $\mathbf{v}$. Hence, the corresponding mean free path is given by

$$l_t(\mathbf{v}) = \frac{1}{\rho \sigma_t(\mathbf{v})}. \quad (17)$$

According to (15), therefore,

$$\frac{1}{l_t(\mathbf{v})} = \frac{1}{l_s(\mathbf{v})} + \frac{1}{l_a(\mathbf{v})}, \quad (18)$$

where the subscripts s and a label the contributions from scattering and absorption as before. The values of the cross sections and mean free paths in some typical moderator materials are given for thermal-neutron energies in Table I. (Here, 1 barn = 100 fm².)

TABLE I. MODERATOR PROPERTIES

Quantity	Units	D ₂ O	H ₂	D ₂
ρ	10 ²² molecules/cm ³	3.32	2.12	2.56
σ_s	barns/molecule	14.5	56.0	8.4
σ_a	barns/molecule	0.00123	0.665	0.00104
l_s	cm	2.08	0.84	4.65

III. THERMAL NEUTRONS

Neutrons in Free Space

Let us begin by considering a system of neutrons in free space. Then $\rho = 0$ and the transport equation (16) becomes

$$\left\{ \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right\} f(\mathbf{r}, \mathbf{v}, t) = 0. \quad (19)$$

The expression

$$f(\mathbf{r}, \mathbf{v}, t) = n_0 w(\mathbf{v}) \quad (20)$$

is a particular solution of (19) that represents a uniform distribution of neutrons with number density n_0 and a normalized velocity distribution $w(\mathbf{v})$:

$$\int w(\mathbf{v}) d\mathbf{v} = 1 . \quad (21)$$

An example of such a distribution is a collimated, monoenergetic beam of neutrons with velocity $\mathbf{v}_0$, for which

$$w(\mathbf{v}) = \delta(\mathbf{v} - \mathbf{v}_0) . \quad (22)$$

The current density is then given by

$$\mathbf{J}(\mathbf{r}, t) = n_0 \mathbf{v}_0 , \quad (23)$$

and the flux by

$$\Phi(\mathbf{r}, t) = n_0 v_0 . \quad (24)$$

In this case, the flux is equal to the magnitude of the current density.

Another example is a system of neutrons in thermodynamic equilibrium at temperature T , for which $w(\mathbf{v})$ is given by the Maxwell-Boltzmann distribution:

$$w(\mathbf{v}) = \left(\frac{m}{2\pi kT} \right)^{3/2} \exp \left(- \frac{m\mathbf{v}^2}{2kT} \right) , \quad (25)$$

where k is Boltzmann's constant. Since $w(\mathbf{v})$ is isotropic, we see that

$$\mathbf{J}(\mathbf{r}, t) = 0 , \quad (26)$$

so that there is now no net transport of neutrons through space, and

$$\Phi(\mathbf{r}, t) = n_0 v_{av} , \quad (27)$$

in which v_{av} is the average neutron speed:

$$v_{av} = \int v w(\mathbf{v}) d\mathbf{v} = \sqrt{\frac{8kT}{\pi m}} . \quad (28)$$

Neutrons in a Moderator

Let us now consider a system of neutrons in a material medium, or moderator. If the linear dimensions of the moderator are sufficiently large in comparison with the mean free path, we can expect that the neutrons will be in thermodynamic equilibrium with the moderator. In the present

case, the phase-space distribution function is governed by Eq. (4) and, if this equation is to have a solution of the type (20), it is necessary that

$$\sigma_a(\mathbf{v}) = 0, \quad (29)$$

and

$$v w(\mathbf{v}) \sigma_s(\mathbf{v}, \mathbf{v}_0) = v_0 w(\mathbf{v}_0) \sigma_s(\mathbf{v}_0, \mathbf{v}). \quad (30)$$

Equation (29) implies that the neutrons cannot be in true thermodynamic equilibrium with an absorbing medium. Equation (30) guarantees that whenever a neutron is scattered from $\mathbf{v}$ to $\mathbf{v}_0$, another is scattered from $\mathbf{v}_0$ to $\mathbf{v}$, so that a stationary equilibrium state is maintained. This relation is accordingly called the *Condition of Detailed Balance*. Since $w(\mathbf{v})$ is assumed to be given by (25), it then follows from (11) that the relation (30) is equivalent to

$$S(-\mathbf{q}, -\omega) = \exp\left(-\frac{\hbar\omega}{kT}\right) S(\mathbf{q}, \omega). \quad (31)$$

This alternative form of the detailed-balance condition can also be derived directly from the quantum-mechanical expression for the dynamic structure factor.^[5]

Thermal-Neutron Flux

The thermal-neutron flux (27) can be denoted simply as Φ because it is independent of $\mathbf{r}$ and t . We can then express it in the form

$$\Phi = \int \Phi(\mathbf{v}) d\mathbf{v}, \quad (32)$$

in which

$$\Phi(\mathbf{v}) = n_0 v w(\mathbf{v}). \quad (33)$$

Since $w(\mathbf{v})$ is isotropic, we can then use (7) to re-express the flux as

$$\Phi = \int_0^\infty \Phi(E) dE, \quad (34)$$

where

$$\Phi(E) = \frac{4\pi v}{m} \Phi(\mathbf{v}) = \frac{4\pi n_0 v^2}{m} w(\mathbf{v}). \quad (35)$$

Let us now write

$$\Phi(E) = \Phi g(E) , \quad (36)$$

in which $g(E)$ is the normalized energy distribution:

$$\int_0^{\infty} g(E) dE = 1 . \quad (37)$$

Using (25), we then find that

$$g(E) = \frac{E}{(kT)^2} \exp\left(-\frac{E}{kT}\right) , \quad (38)$$

and the maximum of this distribution occurs at $E_{\max} = kT$.

Thermal Neutrons in a Reactor

The preceding relations refer to a hypothetical situation in which the neutrons are in thermodynamic equilibrium with a non-absorbing moderator. In reality, the neutron distribution in the moderator of a reactor is the result of a dynamic balance between the fast neutrons entering from the fuel elements and the slow neutrons being lost through leakage and absorption. As a result, the velocity distribution is not strictly Maxwellian and the effective temperature of the thermal neutrons is somewhat higher than the temperature of the moderator. For example, the thermal-neutron flux in a heavy-water reactor^[6] follows the Maxwellian distribution (38) very closely up to energies of about $5kT$, with an effective temperature that is typically 10 to 30 K higher than the temperature of the moderator. Above $5kT$, in the so-called epithermal region, the distribution changes rather abruptly to a characteristic slowing-down spectrum^[7]:

$$g(E) \propto \frac{1}{E} \quad \text{if } E > 5kT . \quad (39)$$

The energy distribution of the flux is illustrated in Fig. 1 for a neutron temperature of 313 K.

Wavelength Distribution

When thermal-neutron beams are used for applications such as neutron diffraction, where quantum effects are important, it is useful to describe the neutrons in terms of the de Broglie wavelength λ . In this case, the momentum and energy relations become

Fig. 1. Thermal-neutron flux as a function of energy.

$$mv = \frac{h}{\lambda}, \quad E = \frac{h^2}{2m\lambda^2}, \quad (40)$$

where h is Planck's constant. The neutron flux can then be expressed as

$$\Phi = \int_0^\infty \Phi(\lambda) d\lambda, \quad (41)$$

where

$$\Phi(\lambda) = \Phi(E) \left| \frac{dE}{d\lambda} \right|, \quad (42)$$

and

$$\left| \frac{dE}{d\lambda} \right| = \frac{h^2}{m\lambda^3}. \quad (43)$$

As before, we can write

$$\Phi(\lambda) = \Phi g(\lambda), \quad (44)$$

where $g(\lambda)$ is the normalized wavelength distribution:

$$\int_0^{\infty} g(\lambda) d\lambda = 1. \quad (45)$$

We then get

$$g(\lambda) = \frac{2\lambda_T^4}{\lambda^5} \exp\left[-\left(\frac{\lambda_T}{\lambda}\right)^2\right], \quad (46)$$

in which λ_T is the wavelength corresponding to an energy kT :

$$\lambda_T = \frac{h}{\sqrt{2mkT}}. \quad (47)$$

The Jacobian (43) has the effect of shifting the intensity toward shorter wavelengths. Consequently, the maximum of the wavelength distribution (46) does not occur at λ_T , but at

$$\lambda_{\max} = \sqrt{\frac{2}{5}} \lambda_T \approx 0.632 \lambda_T. \quad (48)$$

Finally, it follows from (39) that, in the epithermal region,

$$g(\lambda) \propto \frac{1}{\lambda} \quad \text{if } \lambda < \frac{\lambda_T}{\sqrt{5}}. \quad (49)$$

Fig. 2. Thermal-neutron flux as a function of wavelength.

The wavelength distribution of the flux in a heavy-water reactor with a neutron temperature of 313 K is shown in Fig. 2. This temperature corresponds to an energy $kT = 27$ meV, which is the energy of the maximum in Fig. 1, and to a wavelength $\lambda_T = 1.7$ Å. The maximum in Fig. 2 occurs at $\lambda_{\max} = 1.1$ Å.

IV. COLD NEUTRONS

Neutrons with energies less than 5 meV, or wavelengths greater than 4 Å, are conventionally referred to as “cold neutrons”. This rather arbitrary limit is the Bragg cutoff of beryllium, which is commonly used as a filter to produce beams of low-energy neutrons. For many important applications of neutron-beam research, such as small-angle scattering, an adequately intense flux of cold neutrons is needed. However, less than 2% of the total flux in Figs. 1 or 2 is in the cold-neutron region.

Cold Source

The available cold-neutron flux can be increased significantly by installing a cold source in the beam tube such as that indicated schematically in Fig. 3. Such a cold source might, for example, contain liquid hydrogen at 20 K. Thermal neutrons at roughly the temperature of the moderator

Fig. 3. Reactor cold source.

enter the cold source from essentially all directions and lose energy through collisions with the molecules in the source. If the linear dimensions of the source are much larger than the mean free path, the neutrons will tend to acquire a Maxwellian distribution of energies characteristic of the temperature of the source. As a result of the collimator in Fig. 3, the detector only sees neutrons that leak out of the cold source, and the flux of such neutrons below 5 meV can be much larger than for a source at the ambient temperature of the reactor.

Ideal Gain

Let us postulate a situation where the neutrons are simply cooled at constant density from an initial temperature $T_0 = 313$ K to a final temperature $T = 20$ K. The initial and final flux distributions are shown as a function of energy in Fig. 4a, and as a function of wavelength in Fig. 4b. We see that there is indeed a very substantial increase in the neutron flux below 5 meV or above 4 Å. The gain is given as a function of energy by

$$G(E) = \frac{\Phi(E)}{\Phi_0(E)} = \left(\frac{T_0}{T}\right)^{3/2} \exp\left[-\frac{E}{k}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right], \quad (50)$$

and as a function of wavelength by

$$G(\lambda) = \frac{\Phi(\lambda)}{\Phi_0(\lambda)} = \left(\frac{T_0}{T}\right)^{3/2} \exp\left[-\left(\frac{\lambda_T^2 - \lambda_{T_0}^2}{\lambda^2}\right)\right]. \quad (51)$$

The limiting gain as $E \rightarrow 0$ or $\lambda \rightarrow \infty$ is

$$\left(\frac{T_0}{T}\right)^{3/2} = 61.9. \quad (52)$$

The gain is shown as a function of energy in Fig. 4c, and as a function of wavelength in Fig. 4d. These results are, of course, highly idealized. In reality, the source is never large enough to achieve complete rethermalization of the neutrons. Also, the reduction in the flux due to absorption in the source, and in its associated structural components, is not entirely negligible. Nevertheless, gains as large as 20 or more can be achieved in practice, as we shall see later.

V. SMALL-SOURCE GAIN

To demonstrate that complete rethermalization of the neutrons is not, in fact, necessary in order to obtain substantial gains, we shall consider a cold source whose linear dimensions are of the

Fig. 4. Neutron flux and gain for an ideal cold source.

order of the mean free path, so that only single scattering is appreciable. This is then an extreme example of an undermoderated cold source, and the performance of an actual cold source can be expected to lie somewhere between that predicted in the preceding section and the results we shall obtain in this section.

General Formula

We suppose the source is immersed in an isotropic ambient flux $\Phi_0(E)$. Let $Q(E) d\Omega dE$ denote the average number of incident neutrons scattered into the solid angle $d\Omega$ with energy in dE per unit time. Then a simple calculation shows that

$$Q(E) = \frac{N}{4\pi} \int_0^\infty \Phi_0(E_0) \sigma_s(E_0, E) dE_0, \quad (53)$$

where N is the number of atoms in the source and $\sigma_s(E_0, E)$ is the scattering kernel (14). The number of neutrons per unit time that enter the detector in Fig. 3 is then given by

$$\Phi A \frac{d\Omega}{4\pi} = \int_0^\infty Q(E) dE d\Omega, \quad (54)$$

in which Φ is the scattered-neutron flux in the source, A is the area of the source seen by the detector, and $d\Omega$ is the solid angle subtended at the source by the detector. It then follows from (34) that the energy distribution of the source flux is

$$\Phi(E) = \frac{4\pi}{A} Q(E) = \rho d \int_0^\infty \Phi_0(E_0) \sigma_s(E_0, E) dE_0. \quad (55)$$

Here, $\rho = N/V$ is the number of atoms per unit volume in the source, the volume of which is V , and $d = V/A$ is the average thickness of the source along the axis of the beam tube. The gain is therefore given by

$$G(E) = \frac{\Phi(E)}{\Phi_0(E)} = \frac{\rho d}{g_0(E)} \int_0^\infty g_0(E_0) \sigma_s(E_0, E) dE_0, \quad (56)$$

in which $g_0(E)$ is the normalized energy distribution of the incident flux. This quantity is given by the Maxwellian expression (38), in which T is the temperature of the incident neutrons, which is slightly above the ambient temperature in the reactor. The temperature of the cold source itself enters through the scattering kernel $\sigma_s(E_0, E)$. In the remaining sections of this paper we shall calculate the small-source gain (56) for various model scattering kernels.

Bound Atom

Let us begin by considering an isotropic elastic scatterer, like vanadium, for which the dynamic structure factor can be approximated by the bound-atom expression

$$S(\mathbf{q}, \omega) = \delta(\omega). \quad (57)$$

This is, of course, not a very appropriate model for a cold source. It does, however, provide a useful comparison for the models introduced later. In a sense, the bound-atom model (57) plays the same role in "calibrating" the theory that vanadium does in scattering experiments.

The scattering kernel (14) can easily be calculated for the above model, and one finds that

$$\sigma_s(E_0, E) = \sigma_s \delta(E - E_0), \quad (58)$$

and, hence, that the total scattering cross section is

$$\sigma_s(E_0) = \sigma_s. \quad (59)$$

This verifies our assertion in Sec. II that σ_s is the bound scattering cross section. The small-source gain (56) then becomes

$$G(E) = \rho \sigma_s d = \frac{d}{l_s}, \quad (60)$$

which is simply the ratio of the source thickness to the mean free path. Since the scattering is elastic, there is no change in the energy distribution of the neutrons and, hence, the gain is independent of energy. The theory also ignores multiple scattering so that we must, for consistency, assume that $d < l_s$, in which case $G(E) < 1$. In other words, there is no net gain for the present model.

Free Atom

Let us now assume that the cold source is an ideal gas at $T = 0$. In this case,

$$S(\mathbf{q}, \omega) = \delta(\omega - \omega_r), \quad (61)$$

in which $\hbar\omega_r = (\hbar q)^2/2M$ is the recoil energy, and M is the mass of an atom in the gas. The delta function in (61) expresses conservation of energy and momentum in the collision of a neutron with a free atom that is initially at rest.

The scattering kernel (14) is then given by

$$\sigma_s(E_0, E) = \begin{cases} \frac{\sigma_s A}{4E_0}, & \eta E_0 < E < E_0, \\ 0, & \text{otherwise,} \end{cases} \quad (62)$$

where $A = M/m$ is now the atom/neutron mass ratio, and

$$\eta = \left(\frac{A-1}{A+1} \right)^2. \quad (63)$$

According to (62), the incident neutron always loses energy in the collision, and the average energy of the scattered neutron is

$$\bar{E} = \left(\frac{\eta+1}{2} \right) E_0 = \left[\frac{A^2+1}{(A+1)^2} \right] E_0. \quad (64)$$

The ratio $\bar{E}/E_0$ is shown as a function of A in Fig. 5. This ratio is a minimum at $A = 1$ where it has the value 0.5. This figure shows that it is desirable for A to be as close to unity as possible in order to obtain the maximum slowing-down effect. The total scattering cross section (13) for a free atom follows immediately from (62), and we obtain the well-known result^[7]

$$\sigma_s(E_0) = \left(\frac{A}{A+1} \right)^2 \sigma_s. \quad (65)$$

The small-source gain (56) is likewise given for the present model by

$$G(E) = (\rho \sigma_s d) \frac{AkT}{4E} \left\{ 1 - \exp \left[- \left(\frac{4A}{(A-1)^2} \right) \frac{E}{kT} \right] \right\}. \quad (66)$$

The first factor on the right-hand side is the bound-atom gain (60), and the remaining factors

Fig. 5. Average scattered-neutron energy in an ideal gas at $T = 0$.

Fig. 6. Small-source gain for an ideal gas at $T = 0$ and thickness $d = 1/\rho\sigma_s$.

show how the gain is modified by the atomic recoil. The temperature T in the above expression is the temperature of the incident neutrons. The source itself is at $T = 0$ in the present model. When $A = 1$, the expression (66) reduces to

$$G(E) = (\rho\sigma_s d) \frac{kT}{4E}, \quad (67)$$

and when $E = 0$, it becomes

$$G(0) = \rho\sigma_s d \left(\frac{A}{A-1} \right)^2. \quad (68)$$

The small-source gain (66) is shown as a function of E in Fig. 6 for an incident-neutron temperature $T = 313$ K, and for various values of A . The source thickness d is assumed to be equal to the bound-atom mean free path. Quite large gains are obtained below 2 meV when $A = 1$ or 2, but for larger values of A the gain is, at best, marginal.

Liquid Hydrogen

We have recently developed^[8] a simple analytical model for the scattering kernel of a homonuclear diatomic liquid such as H_2 or D_2 . The model assumes that: (i) the molecules are freely rotating, (ii) the intermolecular interference effects can be described by the convolution

approximation, and (iii) the center-of-mass incoherent scattering can be calculated from the impulse approximation. Extensive numerical calculations have been performed for liquid H_2 , liquid D_2 , and mixtures of the two, to determine both the scattering kernel (14) and the total scattering cross section (13) for this model. The results are described in detail in Ref. 8 and illustrate the dependence of the scattering kernel on the incident- and scattered-neutron energies, the behavior near rotational thresholds, the dependence on the center-of-mass pair correlations, the dependence on the ortho concentration, and the dependence on the deuterium concentration in H_2/D_2 mixtures.

Figure 7 shows the small-source gain calculated using the above-mentioned model for liquid parahydrogen and liquid orthohydrogen. The thickness is taken to be 1 cm, roughly the value of the mean free path in liquid normal hydrogen (see Table I). The difference in gain arises because, in parahydrogen, the scattering is mainly due to the $0 \rightarrow 1$ rotational transition, while, in orthohydrogen, the scattering is mainly nonrotational for this energy range. The ortho modification gives a significantly higher gain above 0.5 meV.

The small-source gains calculated for 1 cm of liquid normal hydrogen and 5 cm of liquid normal deuterium are compared in Fig. 8. These thicknesses each correspond to about one mean free path according to Table I. Here, the difference in gain is mainly because the scattering in deuterium depends strongly on the center-of-mass pair correlations, while the scattering in liquid hydrogen is almost entirely independent of these correlations. This behavior is, in turn, caused by

Fig. 7. Small-source gain for liquid ortho and parahydrogen.

Fig. 8. Small-source gain for liquid hydrogen and deuterium.

Fig. 9. Comparison of the equilibrium and small-source gains calculated for a liquid-hydrogen cold source with measured values from Ref. 9.

the fact that deuterium is predominantly a coherent scatterer of neutrons, while the scattering in hydrogen is almost entirely incoherent. Liquid hydrogen gives an appreciably higher gain, especially at low energies.

VI. DISCUSSION

In this paper, we have calculated the behavior of a cold-neutron source for two limiting cases: (i) a large, well-thermalized source in which the neutrons are simply cooled at constant density from the ambient temperature of the reactor to, for example, liquid hydrogen temperature and, (ii) a small, undermoderated source in which the incident neutrons are only scattered once before leaving it. In both cases, we find significant flux gains in the cold-neutron region. In case (i), the gain depends only on the temperature of the cold source and is independent of its size or composition. However, in case (ii), the gain depends strongly on the size and composition of the source as well as on its temperature.

In Fig. 9 we compare the computed gains, as a function of wavelength, in a liquid-hydrogen cold source for the above two cases. We also show the measured gain^[9] for the 4-litre liquid-hydrogen cold source in the Kyoto University Reactor (KUR). Below 6 Å, the measured values roughly

follow the expected equilibrium values, although the former are, in fact, somewhat larger, especially below 4 Å. Above 6 Å, the measurements fall between the two model calculations, which indicates that the thermalization is incomplete at these long wavelengths. The KUR results shown in Fig. 9 are typical of the gains measured in other liquid-hydrogen cold sources.^[10-13]

Although we have used the expression (56) for the small-source gain for thicknesses d of the order of the mean free path l_s , this formula is, in fact, only rigorously correct when $d \ll l_s$. For larger values of d , the effect of multiple scattering and absorption must be taken properly into account by solving the neutron transport equation (4) with a suitable scattering kernel for the boundary conditions appropriate for the geometry of interest. One then finds,^[11,14,15] in agreement with experiment, that when $d > l_s$ the gain in liquid hydrogen does not continue to increase linearly with d , as (56) would predict, but increases less rapidly than this, eventually reaching a well-defined maximum, above which it decreases as the suppression of the flux by neutron absorption in the source becomes significant. The optimum source thickness for liquid hydrogen is found to be roughly 2 to 3 cm. In liquid deuterium, on the other hand, the absorption cross section is extremely small (see Table I) so that the optimum thickness is not sharply defined. With increasing d , the gain essentially saturates at a thickness of about 20 cm.

REFERENCES

1. B. Davison, Neutron Transport Theory, Oxford University Press, 1957.
2. K.M. Case and P.F. Zweifel, Linear Transport Theory, Addison-Wesley, Reading MA, 1967.
3. E. Amaldi, O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti, and E. Segrè, *Proc. Roy. Soc. A* **149**, 522 (1935).
4. S.W. Lovesey, Theory of Neutron Scattering from Condensed Matter, Oxford University Press, 1984.
5. P. Schofield, *Phys. Rev. Lett.* **4**, 239 (1960).
6. C.H. Westcott, *J. Nucl. Energy* **2**, 59 (1955).
7. E. Fermi, *Ric. Sci.* **7**, 13 (1936).
8. V.F. Sears, Atomic Energy of Canada Limited Report, AECL-10056 (1990).
9. M. Utsuro, T. Kawai, Y. Maeda, H. Yamaoka, T. Akiyoshi, and S. Okamoto, *Physica B* **156 & 157**, 540 (1989).
10. F.J. Webb, *J. Nucl. Energy A/B* **17**, 187 (1963).
11. P. Ageron, P. de Beaucourt, H.D. Harig, A. Lacaze, and M. Livolant, *Cryogenics* **9**, 42 (1969).
12. C. Doose, A. Preussner, F. Stelzer, H. Stiller, and A. Tholen, *Cryogenics* **11**, 107 (1971).

13. P. Ageron, In Neutron Scattering in the Nineties, International Atomic Energy Agency, Vienna, 1985, p. 135.
14. P. Carter and D.M. Jones, J. Nucl. Energy **26**, 237 (1972).
15. J.R. Moon and T.D. Beynon, J. Phys. D **6**, 427 (1973).

Neutron Slowing Down and Thermalization

Varley F. Sears

Questions/Answers/Comments

(W. Bernnat)

Question:

How did you evaluate the static structure factor for the convolution approximation (accounting for the intermolecular interface)?

Answer:

What I needed was the static structure factor $S(q)$ for the center-of-mass pair correlations. I used the measured $S(q)$ for liquid neon, and scaled it according to the principle of corresponding states to give me an approximate $S(q)$ for liquid hydrogen.

(F. Bernard)

Question:

What was your criterion for a "small cold source"?

Answer:

It is small if its thickness is smaller than the neutron mean-free path.

Historical Benchmarks and Experimental Problems

Peter Egelstaff
University of Guelph
Ontario, Canada

ABSTRACT

Some historical benchmarks are reviewed and comparisons made between popular cold moderators. The differences between the design criteria for steady state and pulsed source cold moderators will be reviewed and discussed. Outstanding problems for both kinds of sources are listed and some actions proposed.

I. INTRODUCTION

The design of a cold neutron source is a compromise between a variety of properties and objectives, some of which may be in conflict. It is usual to begin with the scattering properties, because in order to study neutron slowing down and moderation in materials, their neutron scattering cross sections (or kernels) need to be known in some detail. These data are usually a combination of experimental and theoretical information (see Egelstaff and Poole^[1]), and are readily tested by a combination of scattering cross section measurements and the measurement of neutron spectra within a (large) assembly of each material or combination of materials. With modern equipment, such measurements^[1] are relatively straightforward, and further discussion of them is outside the scope of this paper. However, for large sources, reasonable calculations may be made using such scattering data.

For small cold neutron sources only a few collisions, between the incoming neutrons and the source material, take place. The source, and its surroundings may have a complex construction with many components which inevitably makes calculations difficult. Even numerical simulations are at best approximate: as output source operating characteristics, cryogenic information and cold neutron performance are needed. There are so many variables and different problems involved that the optimization of these sources is not a simple matter. However, the subject is fairly old and a lot of empirical information is available to help the designers and users. Consequently, it is useful to consider a series of "historical benchmarks" which will show some underlying themes in the forty year history of this subject.

II. HISTORICAL BENCHMARKS

The first liquid hydrogen cold neutron source was tested on the Los Alamos pulsed neutron facility in the mid-1940's (Sutton, et al^[2]). They used a cyclotron proton beam with the Be(p,n) reaction to make a pulsed neutron source, and moderated the neutrons in liquid hydrogen. A gain in intensity of approximately a factor of ten compared to a room temperature paraffin moderator was observed for 20 K neutrons. Also, the neutron temperature from this source was about 100 K. No further information on this source seems to have been published.

The first use of liquid hydrogen in a nuclear reactor to produce cold neutrons was made by Butterworth et. al^[3] in the mid-1950's. In designing their source, they tested a variety of moderators in addition to hydrogen. Table 1 is a summary of these results.

TABLE I.

Apparent Beam Temperatures obtained with Various Moderators (in °K)				
Temperature of Moderator °K				
Moderator	90	77	20	4
Pentane	—	135 ± 14	121 ± 15	—
Methane	135 ± 5	134 ± 7	75 ± 6.5	65 ± 8
Methyl alcohol	—	173 ± 19	135 ± 17	—
Hydrogen deuteride	—	—	77 ± 6	—

It can be seen that methane and HD are the best two examples in the table and that the neutron beam temperatures tend to saturate at lower temperatures. They noted that methane suffers from

radiation damage problems (producing H_2 and polymers) and is a solid at low temperature. Thus they selected liquid H_2 , and Figure 1 shows their "in-pile" apparatus. Significant improvements in cold neutron flux compared to those found with a graphite block in place of the hydrogen source, were observed and are shown in the lower part of the figure. These gains are very useful, but are well below ideal values. Samples with varying ortho/para-hydrogen ratios were tested also, but essentially no dependence on this ratio was found.

Relative efficiency of hydrogen at 25°K and graphite at 400°K in producing cold neutrons.

Fig. 1

Upper diagram: Sketch of the apparatus used by Butterworth, et. al^[3] in the reactor BEPO. The block M was tested as a "Maxwell Demon" reflector, supposedly reflecting unmoderated neutrons back into the hydrogen and allowing cold neutrons to escape down the tube N.

Lower diagram: Flux gain as a function of wavelength observed with the apparatus in the upper diagram compared to its replacement with a graphite block.

Webb^[4] reported some subsequent measurements with this apparatus and his results are shown in Figure 2. It can be seen that the gain ~20 is well below the theoretical limit of 100-200. Again simply reducing the hydrogen temperature is not very advantageous, but solid methane at 22K gives some improvement over hydrogen. This was believed to be due to the fact that the 0-1 rotational transition is ~1 meV in methane compared to ~15 meV in hydrogen.

COLD NEUTRON SOURCES

F. J. WEBB
A.E.R.E., Harwell, Berks.

Fig. 2. Summary of the data of Webb using the apparatus shown in Fig. 1

The conclusion of this program was, therefore, that a successful cold neutron source in a reactor with small beam holes may be made from liquid hydrogen, but its performance was far from the theoretical limit. Taking both the cold neutron gain and the operating difficulties into account, liquid hydrogen was the best choice of the materials considered. The second choice was methane, but its advantages did not outweigh its disadvantages. Although these conclusions were reached more than thirty years ago, they have stood the test of time, being unchanged by the numerous studies of moderating materials made over this period.

A somewhat larger source in a higher power reactor was built by Jacrot and coworkers^[5] for the EL3 reactor in Saclay. This source used a continuously operated refrigeration system compared to the syphon of Butterworth, et. al^[3]. Also being larger, the neutron absorption in hydrogen was too great for optimum performance. Cribier & Jacrot^[5] reported results with varying H/D ratios, and were able to optimize the performance of their source by adjusting this ratio. Thus, two important advances were demonstrated; namely a continuously operated system and the importance of adjusting the H/D ratio to the system size. Van Dingenen and Hautecler^[6a] built a source for testing moderators at the BR1 reactor at Mol and studied the properties of methane moderators in detail. The advantages of liquid methane for neutrons of $\sim 3 \text{ \AA}$ were pointed out. McReynolds and Whittemore^[6b] built a large pulsed neutron source (about 2.5 l) for an electron linac and compared a cold ice source with liquid hydrogen. Their results are shown in Figure 3, for both moderators at a temperature of 20 K. In the case of liquid H_2 , they fitted the data to a neutron temperature of 30K from 4 to 25 $\text{\AA}$. Over the same range, the cold ice results varied from about equal to about 1/10 the intensity. These results (among others) demonstrated the importance of low lying energy levels in achieving good moderation.

Fig. 3 Data of McReynolds and Whittemore^[6b] on H_2O ice and liquid H_2 using a large (2.51) moderator.

COLD NEUTRON SOURCES OF LIQUID HYDROGEN AND LIQUID DEUTERIUM

P. AGERON,¹ Ph. De BEAUCOURT,² H. D. HARIG,³ A. LACAZE,⁴ and M. LIVOLANT⁵

Figure a. Flux gain factor by cold neutron source of annular layer of liquid normal hydrogen

Figure b. Flux gain factor by cold neutron source of liquid deuterium (cell of 18 cm dia)

Figure c. Flux gain factor by cold neutron source of liquid deuterium (cell of 38 cm dia)

Fig. 4 Examples of the work of Ageron, et. al.^[10] on: a) liquid hydrogen, b) liquid deuterium 18 cm diam, and c) liquid deuterium 38 cm diam.

Para-H₂ had been expected to be advantageous in the early studies, because below the lowest rotational transition, its cross section falls off. This, it was thought, could allow cold neutrons to escape preferentially. However, no large effects were found^[4,7] during this period. Later, this effect was shown clearly in the work of Valo^[8] on the FIRI reactor at Espoo. He used a long (35 cm by 10 cm dia.) source and observed neutrons down the long dimension. At 4 Å, the intensity was a factor of two greater for a 1.5% ortho in para sample compared to a 50/50 mixture.

The above studies covered the salient features of cold neutron sources, and led quickly to interpretive work and proposals for improvements. This phase has proved to be an extended one, and is still unfinished.

III. DISCUSSION OF MODERATOR DESIGNS

The work of Butterworth et. al^[2] gave results that were fairly independent of some variables (e.g., lower temperatures, ortho/para ratio). It was realized that this was due partly to the albedo effect, that is, a significant contribution to the cold neutron spectrum came from neutrons which had scattered off the face of the source being viewed, or which had otherwise suffered only very few collisions in the hydrogen. In order to increase the number of collisions, designs involving re-entrant holes or composite structures were considered but were not pursued, partly because these designs needed larger holes in the reactor and partly because of the mechanical and cryogenic consequences.

However, two proposals arose out of these early studies at Harwell. For holes in existing reactors, an inexpensive but reliable source could be made using super-critical hydrogen (Webb & Pearce^[9]). The hydrogen density could be maintained at a reasonable level while the operational advantages of a single phase (gaseous) system would be exploited and the energy loss per collision was good. Nevertheless, there would be some sacrifice of gain factors, partly through using a thick pressure vessel for the moderator and partly because of lower density and higher temperature for the hydrogen.

At about this time, the results from the BEPO experiments were being interpreted and the new reactor DIDO was being designed. This raised the question of how to design a source for a new reactor. It was realized that there were two important requirements which should be met in order to raise the gain factors. These were to increase the number of inelastic collisions and to reduce the nuclear absorption. Both objectives might be realized if a large volume liquid D₂ source could be installed in a new reactor. Simple calculations suggested these arguments were reasonable, but no

experimental measurements were made. Partly for reasons of cost, partly for reasons of time, and partly for the reactor and cryogenic engineering problems, this proposal was not adopted.

As a summary of the experiments and studies outlined above, the main properties of interest may be listed and compared for the two favorite moderators. This comparison is made in table 2. The properties which especially favor hydrogen or deuterium are the low mass, the low viscosity, the negligible radiation damage, and the useful liquid range. The disadvantages of hydrogen, compared to methane, lie in its lower hydrogen density and higher energy rotational states.

TABLE II
FAVORITE MODERATORS COMPARED

Item	Hydrogen	Methane	Advantage
Cross Section	Large	Twice as Large	Methane
Number Density	Slightly Larger	Slightly Smaller	Hydrogen
Effective Mass	Low in Liquid	Low at high E_N High at low E_N	Hydrogen
Viscosity of Liquid	Nearly quantum	Higher	Hydrogen
Radiation Damage	Nil	Polymers & Hydrogen	Hydrogen
Fast Neutron and γ -ray heat	Smaller	Larger	Hydrogen
Liquid Range	>14 K	>89 K	Hydrogen
Cold Neutron Escape	Para-Hydrogen	Not Available	Hydrogen
Deuterated Source	Very Good With Reactor	Rarely Used	Hydrogen
Lowest Rotation in Ideal Plastic Crystal	15 meV	1 meV	Methane
Safety mixture with Oxygen	4% to 74% Explosive	Smaller	Methane

The question of a large liquid deuterium source was reopened during the discussions for an OECD European Reactor, in 1961-1963. The neutron physicists insisted that it be included in this design, in spite of the objections of the reactor engineers who wanted more test experiments and design data to be obtained. Unfortunately, this reactor project was abandoned in 1963.

However, work on this type of source was resumed when the French-German reactor project at the Institut Laue-Langevin was started. A series of definitive studies was conducted by Ageron, et. al^[7], and which demonstrated clearly the advantages of this concept. Some of their results are given in Figure 4. In the best-case gain factors ~ 100 were obtained, and in due course a source of this kind was built into the ILL high flux reactor. As a result of these tests and the performance of their source, it may be concluded that a large liquid D_2 source is the correct choice for a new reactor. Moreover, the large size allows scope for re-entrant holes, composite designs, or other features to be incorporated in situations where that is worthwhile.

On the other hand, for pulsed sources the questions facing the designer cannot be resolved in a similar way. The reasons are that the moderator must be small and must generate a suitable pulse length or shape as well as a copious supply of cold neutrons. During the 1960's, extensive studies of the design of moderators for pulsed neutron sources were carried out by groups using electron linacs. The work of Michaudon^[10] on intense short pulses, the work of Poole^[1] on pulse shapes in the thermal region, and the work of Fluharty^[11] on the changes in pulse shape as E_N approaches $k_B T$ may be mentioned. These studies are beneficial to the designers of moderators for any new generation of pulsed sources.

Efficient slowing down is a very important requirement for pulsed source moderators, and this property alone has been sufficient to make all designers choose hydrogen. Because neutron pulse lengths are controlled, in many cases, by leakage from the moderator, it is possible to tolerate larger absorption factors in this case than for reactor moderators. Thus, the absorption in hydrogen is not a matter of concern. In addition, the toleration of greater absorption allows more structural material to be used, and hence, special geometries have been tried (e.g., the grooved moderator of Ishikawa et. al^[12]). Also, multistage moderators with decouplers between the stages are useful in controlling the pulse shape by absorption as well as leakage.

Fluharty's^[11] measurements on pulse shapes for room temperature hydrogenous moderators show that an experimentalist should select $E_N > 10k_B T$ for sharp pulses. That is during the process of fast neutron slowing down, only "down-scattering" of neutrons occurs and the pulses remain sharp until E_N approaches the thermal range. Then both "up-scattering" and "down-scattering" occur and the pulse shape deteriorates, first by broadening at the trailing edge and subsequently by broadening at the leading edge as well. The effect of "up-scattering" may be seen if E_N falls below $10k_B T$, and this was confirmed in the measurements of pulse shapes in 100 K methane by Carpenter et. al^[13]. In some analyses of data, the resolution provided by a sharp leading edge is exploited, and hence, it is fortunate that this is preserved to lower energies. In other cases, the

total intensity in the pulse is emphasized and then both edges of the pulse are allowed to deteriorate in favor of the pulse area. For such cases it is sometimes better to use a hot moderator.

Thus, the experimental requirements facing designers of cold moderators in steady state and pulsed sources can be different. Table 3 is a comparison of these requirements and illustrates the difficulty in reaching any simple conclusion, other than that both kinds of sources prefer hydrogen.

TABLE III
REQUIREMENTS FOR COLD SOURCES COMPARED

Category	Steady State [e.g. Reactor]	Pulsed Source [e.g. Proton Beam]
Energy Levels	Free particle the best	Free particle the best
Chemical Elements	Lightest	Lightest
Importance of H-density	Can trade-off if volume is large	Should be maximized
Absorption	Minimum	Possible
Poisons	No	Yes
Constructional Materials	Minimum possible	More than reactor OK
Heat Removal	May be large	Lower than reactor
Volume	The larger the better	Usually small
1/E Spectrum	No interest	Very Important
Fast Neutron Flux	Reduce to Low Heat	Of Less Concern
Reflectors	Reactor Moderator	Useful Sometimes
Decouplers	No	Yes
Leakage	No	Yes

IV. LIST OF EXPERIMENTAL PROBLEMS

In tables 2 and 3, a total of 24 properties are listed, and the designer needs to produce an optimum balance between them. The long history of this field can provide many guidelines through the numerous test experiments and examples of working moderators. Even so, more idealized experiments would be worthwhile to test calculations, particularly for somewhat idealized moderators (which would be more amenable to calculation). In recent years computer emulations

of complex assemblies have been more successful due to improvements in hardware, and this trend will undoubtedly continue for some time.

The essential object of any program of experimental tests and calculations is to understand the processes occurring in sufficient detail that design improvements can be made. Just fitting the data by a theory is not enough. It is possible to enumerate the problems which need to be tackled this way, and this is done in table 4.

TABLE IV
List of Problems

1. Lower limits to neutron temperature
2. Size: Maximum output for minimum size
multiple temperature moderators
3. Effects at boundaries:
spectra
decouplers
reflectors
Maxwell demons, etc
4. How to use methane? CH_4 , CD_4 , etc.
5. How to use para- H_2 ? Ortho- D_2 ?
6. Generation of short pulses
 $E_N > 10 k_B T$
poisons
leakage
7. Generation of intense pulses
8. Encyclopedia of Literature
40 years and still growing
Historical benchmarks still useful.

The guidelines and benchmarks which will help the designer may be found in the literature, but unfortunately, this literature extends over forty years and is spread among many subject areas. Consequently, at the present stage this workshop needs an Encyclopedia of the literature in order to perform its tasks properly, and to tackle the problems listed in table 4 efficiently.

The fact that activity in this field has been nearly continuous over such a long period, and today shows no sign of abating, illustrates both the variety of the problems and the breadth of the interest in them. The information handling, distribution, and regeneration problem should itself be added to the above list. Maybe it has become the problem of highest priority.

V. REFERENCES

1. P. A. Egelstaff and M. J. Poole "Neutron Thermalization," Pergamon Press (Oxford) 1969.
2. R. B. Sutton, T. Hall, E. E. Anderson, M. S. Bridge, J. W. DeWire, L. S. Lavatelli, E. A. Long, T. Snyder, and R. W. Williams, *Phys. Rev.*, 72, 1147 (1947).
3. I. Butterworth, P. A. Egelstaff, H. London, and F. J. Webb, *Phil. Mag.*, 2, 917, (1957).
4. F. J. Webb, *Nuclear Science & Engineering*, 9, 120, (1961) and *J. Nuclear Energy A/B*, 17, 187 (1963).
5. B. Jacrot, I.A.E.A. Proceedings, "Pile Neutron Research in Physics", p. 303 (1961) and D. Cribier, B. Jacrot, A. Lacaze, and P. Roubeau, "Inelastic Neutron Scattering in Solids and Liquids," p. 411 (1961).
- 6a. W. Van Dingenen and S. Hautecler, I.A.E.A. Proceedings, "Neutron Inelastic Scattering in Solids and Liquids," p. 453 (1961).
- 6b. A. W. McReynolds and W. L. Whittemore, IAEA publication "Inelastic Scattering of Neutrons in Solids and Liquids," p. 421 (1961).
7. P. Ageron, P. DeBeaucourt, H. D. Harig, A. Lacaze, and M. Livolaut, *Cryogenics*, 9, 42 (1969).
8. M. J. Valo, I.A.E.A. Publication "Inelastic Scattering of Neutrons," p. 77 (1977).
9. F. J. Webb and D. Pearce, Unpublished Harwell Report.
10. A. Michaudon, *J. Nucl. Energy*, 17, 165 (1963).
11. R. Fluharty, *Nucl. Science & Engineering* (1966).
12. Y. Ishikawa, S. Ikeda, N. Watanabe, K. Kondo, K. Inoue, Y. Kiyanagi, H. Iwasa and K. Tsuchihashi, AECL 8488, Report of ICANS VII, p. 230 (1983).
13. J. M. Carpenter, R. A. Robinson, and A. D. Taylor, AECL 8488, Report of ICANS VII, p. 236 (1983).

Historical Benchmarks and Experimental Problems

Peter A. Egelstaff

Questions/Answers/Comments

(R. Pynn)

Question:

All of your remarks have applied only to moderators made of one material. Do you have any comments about mixtures of materials—either homogeneous or heterogeneous? Could such moderators be used to advantage either at reactors or spallation sources?

Answer:

Mixtures of H₂ and D₂ are used widely. Also, if solutions of CH₄ in liquid H₂ (possibly at or slightly above the critical point) occur in nature, they may be useful. Because of the freezing out of rotations in CH₄ near 20K in the solid structure, mixtures of Kr-86 in solid methane (about 17% molecular composition) have been suggested. The specific heat of such mixtures shows that the transitions move down in temperature as Kr is added, falling to zero at 17%.

Multistage moderators have been suggested. In some sense, all systems are two stage—the original material in which the cold moderator is embedded is one and the moderator is the other. However, it has been suggested that the amount of low-temperature material could be reduced if another moderator at an intermediate temperature were employed. You can think of Maxwell Demon devices in this category, too. Pulsed sources employing slowing down in lead have been suggested, and a heavy reflector may be one component of a pulsed source.

(T. Springer)

Question:

Your list of items could also include re-entrant hole sources, or grooves. In this respect, let me ask: is a re-entrant hole efficient if there is no flux gradient over the source?

(P. Ageron)

Comment:

Gain expected from a cavity is due to the fact that the cooling of neutrons is better inside the moderator volume. A gradient, if it exists, also contributes to the gain.

Answer:

I agree with Ageron's comment.

(P. Brewster)

Comment:

On the subject of "an encyclopedia"—at AECL, I have prepared a list of 130 reports and journal articles dealing with cold sources in reactors. This is two years old and may be available as a report upon request.

Cold Moderator Scattering Kernels

Robert E. MacFarlane

Los Alamos National Laboratory
Los Alamos, New Mexico USA

ABSTRACT

Methods now available for generating cold-moderator scattering kernels for liquid and solid methane, liquid ortho and para hydrogen, and liquid ortho and para deuterium are reviewed, including recent improvements in the hydrogen and deuterium models.

I. INTRODUCTION

Accurate scattering kernels for cold moderator materials are important for the design of good experimental facilities. In support of the LANSCE effort, our group in the Theoretical Division developed kernels for solid methane, liquid methane, liquid ortho and para hydrogen, and liquid ortho and para deuterium that were reported on at the ICANS-X meeting.¹ This talk reviews this work and describes recent work at other laboratories that will allow the hydrogen and deuterium data to be improved. First, we will discuss the basic theory behind the new LEAPR module of the NJOY nuclear data processing system,² and then we will discuss the current methods used for each of the the moderator systems. The graphics for this written version of the talk were prepared from the transparencies, and we apologize for the poor quality of some figures that could not be regenerated in better form.

II. LEAPR THEORY

LEAPR is based on the LEAP+ADDELT code originally written by R. C. F. McLatchie at Harwell and A. T. Butland at Winfrith, and modified for cold moderator work by D. Picton, now at the University of Manchester.^{3, 4, 5} It has been further modified at Los Alamos to fit into the NJOY scheme for processing nuclear data and to include new capabilities for handling diffusive effects in liquids, coherent and incoherent elastic scattering, and the interesting quantum effects found in ortho and para hydrogen or deuterium.

The double-differential cross section for neutron scattering is represented in terms of a scattering law using the conventional formula

$$\sigma(E \rightarrow E', \mu) = \frac{\sigma_b}{2kT} \sqrt{\frac{E'}{E}} e^{-\beta/2} S(\alpha, \beta), \quad (1)$$

where the dimensionless momentum and energy transfer parameters are given by

$$\alpha = \frac{E' + E - 2\sqrt{E'E}\mu}{AkT}, \quad (2)$$

and

$$\beta = \frac{E' - E}{kT}. \quad (3)$$

The development depends heavily on the incoherent approximation. If the spectrum of allowed excitations in the materials can be decomposed into a sum over particular types of excitations of the form

$$\rho(\beta) = \sum_{j=1}^K w_j \rho_j(\beta), \quad (4)$$

the scattering law for the materials can be expressed as a convolution of the scattering laws for the separate types of excitation as follows:

$$S(\alpha, \beta) = S^{(K)}(\alpha, \beta), \quad (5)$$

$$S^{(J)}(\alpha, \beta) = \int_{-\infty}^{\infty} S_J(\alpha, \beta') S^{(J-1)}(\alpha, \beta - \beta') d\beta', \quad (6)$$

where S_J is the scattering law for partial spectrum J , and $S^{(J-1)}$ is the composite scattering law including all partial distributions with $j < J$. With this approach, the effects of each of the separate excitation types are "convolved" into S one at a time.

The types of excitations that must be considered are summarized in Figures 1 through 3 (which were reproduced from the transparencies used in the talk). For gas molecules with N atoms, there are $3N$ degrees of freedom (three translations several vibrations, and several rotations), all of which have discrete energies in a frequency spectrum plot like the one shown in Fig. 1. For solids, the molecular vibration modes often remain fairly discrete, but the translation and rotation modes merge into a complex spectrum of lattice vibrations and hindered rotations, which can be represented by the dispersion curves measured by inelastic

neutron scattering and by the frequency spectrum. There is also a component of elastic scattering from the entire lattice. These features are illustrated in Fig. 2. The situation is more complex for liquids. It is often convenient to think of a liquid as little groups of partially-ordered molecules interacting with each other. The chunks act much like solids with modes that show normal lattice vibrations and hindered rotations. The interaction between the chunks leads to diffusive effects; for example, a broadened quasi-elastic peak replaces the sharp elastic peak in neutron scattering experiments. See Fig. 3. Finally, there are also collective effects that have to be considered in some cases. They result from the coherent scattering from atoms of the molecule, which is neglected in the normal incoherent approximation. As shown in Figure 4, coherent interference between waves scattering by the different atoms in one molecule leads to intra-molecular coherent scattering, and if the positions of different molecules are correlated in some way, inter-molecular coherent scattering can occur.

The parts of the excitation spectra discussed above that are due to lattice vibrations and hindered rotations are treated using the phonon expansion method in the LEAP approach. They can also be treated by the time integration approach used in the GASKET code,⁶ but we have found that the LEAP approach is faster, and that it is more stable for the very large α and β values prevalent in cold materials. This method was discussed in detail in the previous report.¹ The results are summarized by the following equations:

$$S_s(\alpha, \beta) = e^{-\alpha\lambda} \sum_{n=0}^{\infty} \frac{1}{n!} [\alpha B]^n T_n(\beta), \quad (7)$$

where

$$\lambda = \int_{-\infty}^{\infty} P_s(\beta) e^{-\beta/2} d\beta \quad (8)$$

is the Debye-Waller factor,

$$B = \int_{-\infty}^{\infty} P_s(\beta) d\beta, \quad (9)$$

is a constant,

$$T_0(\beta) = \delta(\beta), \quad (10)$$

$$T_1(\beta) = \frac{1}{B} P_s(\beta), \quad (11)$$

and in general,

$$T_n(\beta) = \int_{-\infty}^{\infty} T_{n-1}(\beta') T_1(\beta - \beta') d\beta'. \quad (12)$$

GASES

Figure 1: Types of excitations in gases.

SOLIDS

Figure 2: Types of excitations in solids.

LIQUIDS

Figure 3: Types of excitations in liquids.

COLLECTIVE EFFECTS

Figure 4: Collective effects due to coherent scattering.

In these formulas,

$$P_s(\beta) = \frac{\rho_s(\beta) e^{-\beta/2}}{2\beta \sinh(\beta/2)}. \quad (13)$$

where $\rho_s(\beta)$ is the excitation spectrum for the solid-type modes for the material.

The equations used to add in the effects of diffusive modes are

$$S_d(\alpha, \beta) = \frac{2d\alpha}{\pi} e^{2dc\alpha} \frac{\sqrt{c^2 + .25}}{\sqrt{\beta^2 + 4d^2\alpha^2}} K_1 \left\{ \sqrt{c^2 + .25} \sqrt{\beta^2 + 4d^2\alpha^2} \right\}, \quad (14)$$

$$\rho_d(\beta) = \frac{4d}{\pi\beta} \sqrt{c^2 + .25} \sinh(\beta/2) K_1 \left\{ \sqrt{c^2 + .25} \beta \right\}. \quad (15)$$

and

$$S(\alpha, \beta) = S_d(\alpha, \beta) + \int_{-\infty}^{\infty} S_d(\alpha, \beta') S_s(\alpha, \beta - \beta') d\beta'. \quad (16)$$

The scattering law for a discrete oscillator is given by

$$S_i(\alpha, \beta) = e^{-\alpha\lambda_i} \sum_{n=-\infty}^{\infty} I_n \left(\frac{w_i\alpha}{\beta_i \sinh(\beta_i/2)} \right) \delta(\beta - n\beta_i), \quad (17)$$

where

$$\lambda_i = w_i \frac{\coth(\beta_i/2)}{\beta_i}, \quad (18)$$

The delta function makes it easy to compute the convolution indicated by Eq. (6).

III. SOLID METHANE

The excitations used in the analysis for solid methane included the following four optical modes:

energy (eV)	weight
162	.308
190	.186
361	.042
374	.144

The continuous part of the excitation spectrum was obtained from inelastic scattering measurements by Harker and Brugger;⁷ it is shown in Figure 5. The final component is an elastic mode treated in the incoherent approximation because of the large incoherent cross section of hydrogen.

The results of the LEAPR calculation were checked by making sure that various moment conditions were satisfied and making sure that the grids used

Figure 5: Frequency distribution used for solid methane.

for α and β were fine enough to show the main features of the scattering law. Figure 6 gives a sample of the $S(\alpha, \beta)$ results. LEAPR writes out the scattering law in ENDF-6 format,⁸ ready for use in a processing code like NJOY. The processing code can then calculate the integrated cross section $\sigma(E)$ and the energy-to-energy scattering matrix by Legendre order $\sigma_\ell(E \rightarrow E')$. Examples are shown in Figures 7 and 8.

IV. LIQUID METHANE

The model for liquid methane uses the same four discrete oscillators used for solid methane. The continuous excitations and the diffusive part were obtained by combining a hindered oscillator model by Agrawal and Yip⁹ with results obtained from infrared data by Ewing.¹⁰ The result for the continuous part is shown in Figure 9. The weights of the various components are 1.5% for diffusion, 30.5% for rotations, and 68% for molecular vibrations. Some results for the scattering law are shown in Figure 10. The behavior for small α and β is very different from that seen for the solid in Fig. 5. This difference is due to the diffusive component. The integrated cross section and the outgoing neutron distributions are shown in Figures 11 and 12. The prominent quasi-elastic peaks

Figure 6: Scattering law for solid methane at three different energy transfers.

Figure 7: Integrated cross section for inelastic (solid) and incoherent elastic (dashed) for solid methane.

Figure 8: Spectrum of outgoing neutrons from scattering in solid methane for incident energies of 0.001, .0253, and .503 eV.

in Fig. 12 are also due to the diffusive component.

V. LIQUID HYDROGEN AND DEUTERIUM

Hydrogen and deuterium molecules violate the assumption that spins are random that allows the incoherent approximation to be used. An explicitly quantum-mechanical formula is required to account for spin correlations. The formula used in LEAPR is based on the work of Young and Koppel,¹¹ which can be expressed in the following form:

$$S_{\text{para}}(\alpha, \beta) = \sum_{J=0,2,4,\dots} P_J \quad (19)$$

$$\times \frac{4\pi}{\sigma_b} \left[a_c^2 \sum_{J'=0,2,4,\dots} + a_i^2 \sum_{J'=1,3,5,\dots} \right] (2J' + 1) \quad (20)$$

$$\times S_f(\alpha/2, \beta + \beta_{JJ'}) e^{-\beta_{JJ'}/2} \quad (21)$$

$$\times \sum_{\ell=|J'-J|}^{J'+J} 4j_\ell^2(y) C^2(JJ'\ell; 00), \quad (22)$$

Figure 9: Continuous part of the excitation spectrum for liquid methane.

Figure 10: Scattering law for liquid methane at four different energy transfers. Note the diffusive behavior for small α and β .

Figure 11: Integrated cross section for liquid methane compared to experimental data at 100 K.

Figure 12: Spectrum of outgoing neutrons from scattering in liquid methane for incident energies of 0.001, .0253, and .503 eV.

and

$$S_{\text{ortho}}(\alpha, \beta) = \sum_{J=1,3,5,\dots} P_J \quad (23)$$

$$\times \frac{4\pi}{\sigma_b} \left[\frac{a_i^2}{3} \sum_{J'=0,2,4,\dots} + \frac{3a_c^2 + 2a_i^2}{3} \sum_{J'=1,3,5,\dots} \right] (2J' + 1) \quad (24)$$

$$\times S_f(\alpha/2, \beta + \beta_{JJ'}) e^{-\beta_{JJ'}/2} \quad (25)$$

$$\times \sum_{\ell=|J'-J|}^{J'+J} 4j_\ell^2(y) C^2(JJ'\ell; 00), \quad (26)$$

where

$$y = \frac{\kappa a}{2} = \sqrt{4MkT\alpha/2} \quad (27)$$

Similar results with different coefficients hold for liquid deuterium. The original work assumed free-gas scattering

$$S_f(\alpha, \beta) = \frac{1}{\sqrt{4\pi\alpha}} \exp\left[-\frac{\alpha^2 + \beta^2}{4\alpha}\right], \quad (28)$$

but more recently Utsuro at Kyoto University¹² and Keinert and Sax at Stuttgart¹³ have proposed models that include diffusion and hindered rotation terms in place of the free-gas scattering law S_f . We follow the Stuttgart approach. A cluster of maybe 20 molecules is assumed to diffuse through the liquid as a unit. Each molecule in the clump can undergo vibrations very similar to those in a solid. In fact the spectrum used (see Fig. 13) was based on the spectrum for solid hydrogen. The final distribution between the modes is .25% for diffusion, 47.5% for the solid-like spectrum, and 50% for the intra-molecular vibrations. The resulting integrated cross sections for ortho and para hydrogen are shown in Figure 14 compared to data. The additional curves and comparisons to data shown in Figure 15 were taken from the work of Keinert and Sax. Outgoing neutron distributions for both the ortho and para states are shown in Figure 16.

This was the status of the cold-moderator scattering kernel work as of the ICANS-X conference. A study of Fig. 16 shows that the agreement between theory and experiment was fairly good, except for the additional dip in the para hydrogen cross section below 3 meV. The Stuttgart group has recently shown that this dip is due to inter-molecular coherent scattering.

As discussed earlier, inter-molecular coherence results when there is a correlation between the positions of nearby molecules. This kind of coherence is

Figure 13: Continuous part of the excitation spectrum for the effective translational term for liquid hydrogen.

Figure 14: Effective translation scattering law for liquid hydrogen for α values of 0.1, 1.0, and 10 (solid) compared with the free-gas results used in the original Young and Koppel theory.

Figure 15: Integrated cross section for para and ortho hydrogen compared to experimental data. The data for ortho hydrogen (upper curve) was for a gas at 20 K; the lower data is for liquid para hydrogen at 20 K.

described by the “static structure factor” $S(\kappa)$. The values for the static structure factor in hydrogen and deuterium recommended by the Stuttgart group are shown in Figure 18. They use these data in an approximation due to Vineyard as follows:

$$\frac{d^2\sigma}{d\Omega d\epsilon} = \frac{d^2\sigma_{\text{coh}}}{d\Omega d\epsilon} S(\kappa) + \frac{d^2\sigma_{\text{incoh}}}{d\Omega d\epsilon}, \quad (29)$$

to obtain the results shown in Figures 19 through 22.

The results shown in these figures demonstrate that the problem of computing good results for cold-neutron scattering in ortho and para hydrogen have been solved. The IKE Stuttgart results are available from their institute in ENDF-6 format. In addition, the THERMR module of the NJOY system has been upgraded to use their latest method.

Figure 16: Integrated cross section for para and ortho hydrogen compared to experimental data (after Keinert and Sax¹³).

Figure 17: Spectrum of outgoing neutrons from scattering in liquid ortho and para hydrogen are given for incident energies of 0.001, .0253, and .503 eV.

Figure 18: Static structure factor $S(\kappa)$ in liquid hydrogen (H_2) and deuterium (D_2).

Figure 19: Integrated cross section for para and ortho hydrogen computed including inter-molecular coherence at 14 K.

Figure 20: Ortho (top) and para (bottom) H (in H₂) computed including inter-molecular coherence at 19.8 K.

Figure 21: Integrated cross section for para and ortho deuterium computed including inter-molecular coherence at 19.0 K.

Figure 22: Para (top) and ortho (bottom) D (in D₂) computed including inter-molecular coherence at 19.0 K.

VI. REFERENCES

1. Robert E. MacFarlane, "Cold Moderator Scattering Kernels," in *Advanced Neutron Sources 1988, Proceedings of the 10th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X) held at Los Alamos, 3-7 October 1988*, Institute of Physics Conferences Series Number 97 (Institute of Physics, Bristol and New York, 1988), p. 157.
2. R. E. MacFarlane, D. W. Muir, and R. M. Boicourt, "The NJOY Nuclear Data Processing System, Volume I: User's Manual," and "The NJOY Nuclear Data Processing System, Volume II: The NJOY, RECONR, HEATR, and THERMR Modules," Los Alamos National Laboratory reports LA-9303-M, Vols. I and II (May 1982). R. E. MacFarlane and D. W. Muir, "The NJOY Nuclear Data Processing System, Volume III: The GROUPE, GAMINR, and MODER Modules," Los Alamos National Laboratory report LA-9303-M, Vol. III (October 1987). D. W. Muir and R. E. MacFarlane, "The NJOY Nuclear Data Processing System, Volume IV: The ERRORR and COVR Modules," Los Alamos National Laboratory report LA-9303-M, Vol. IV (December 1985).
3. R. C. F. McLatchie, 1962, unpublished.
4. A. T. Butland, "LEAP and ADDELTA, A Users Guide to Two Complementary Codes on the ICL-470 for Calculating The Scattering law From a Phonon Frequency Function," Atomic Energy Establishment Winfrith report AEEW-M-1200, 1973.
5. Private communication from D. J. Picton to G. J. Russell, September 1987.
6. J. U. Koppel, J. R. Triplett, and Y. D. Naliboff, "GASKET, A Unified Code for Thermal Neutron Scattering," General Atomic report GA-7417 (Rev.) (March 1967).
7. Y. D. Harker and R. M. Brugger, "Investigation of the Low-Temperature Phase Transitions in Solid Methane by Slow Neutron Inelastic Scattering," *J. Chem. Phys.* **46**, 2201(1967).
8. P. F. Rose and C. L. Dunford, Eds., "ENDF-102, Data Formats and Procedures for the Evaluated Nuclear Data File, ENDF-6," Brookhaven National Laboratory report BNL-NCS-44945 (July 1990). This is an informal limited-distribution report available from the National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY.
9. Ashok K. Agrawal and Sidney Yip, "Slow-Neutron Scattering by Molecular Liquids," *Nucl. Sci. Eng.* **37**, 368(1969).
10. G. E. Ewing, *J. Chem. Phys.* **40**, 179(1964).
11. James A. Young and Juan U. Koppel, *Phys. Rev.* **135**, A603(1964).
12. Masahiko Utsuro, *Z. Physik B* **27**, 111(1977).
13. J. Keinert and J. Sax, "Investigation of Neutron Scattering Dynamics in Liquid Hydrogen and Deuterium for Cold Neutron Sources," *Kerntechnik* **51**, 19 (1987).

Cold Moderator Scattering Kernels

Robert MacFarlane

Questions/Answers/Comments

(M. Utsuro)

Question:

Are your calculations of the scattering kernels for LH_2 and LD_2 consistent with the compressibilities of these liquids? (In the meaning of parameters used in the calculations).

Answer:

I don't know. Most of the model parameters were obtained directly from IKE.

(P. Egelstaff)

Question:

Have we tried to compare calculations of various real cold sources (like the French work reported by Ageron)?

Answer:

No, we haven't. I would prefer to compare to more differential measurements. It's too hard to tell where the problems are when they have been averaged over an entire cold source design. We need some additional modern measurements, especially for LD_2 at low energies.

(P. Egelstaff)

Question:

The Sköld modification to the Vineyard approximation yields the correct second moment and should be included if possible. Also, these kernels should be used to predict the results published by Ageron on large D_2 and H_2 systems in Siloette during the 60s.

Answer:

Kernels for LH_2 and LD_2 do not satisfy these conditions because the systems are not in equilibrium. Para and ortho can change into each other irreversibly. We do not attempt to satisfy the symmetry of $S(\alpha, \beta)$, its normalization, and the first moment as well as possible for other materials.

(V. Sears)

Question:

The convolution approximation, which you use, is known to be rather inaccurate. So the fact that your calculated total cross section agrees with the data may not guarantee that the model is good because the cross section (σ_t) is not very sensitive to the detailed shape of $S(\alpha, \beta)$. Would you agree with this remark?

Answer:

This model provides a great improvement for liquid deuterium. We would need to make more comparisons with experiments to see what other problems it has.

Cross-Section Libraries and Kerma Factors

Robert C. Little
Robert E. MacFarlane
Robert E. Seamon

Los Alamos National Laboratory
Los Alamos, New Mexico USA

ABSTRACT

A large amount of data is required in order to accurately simulate various aspects of Cold Neutron Sources using radiation transport codes such as MCNP and TWODANT. In particular, the following types of data are needed: coupled neutron/photon transport libraries, neutron thermal $S(\alpha, \beta)$ data, response function data (including energy deposition), and proton interaction data. This paper concentrates on the coupled neutron/photon transport libraries and energy deposition. Another paper at this Conference goes into depth on neutron thermal $S(\alpha, \beta)$ data.

Data libraries available to radiation transport codes are obtained as a result of efforts in many areas, including differential and integral measurements, theoretical model codes, data evaluations, data processing, and data testing. A wide variety of data libraries are available to users of radiation transport codes, including pointwise and multigroup libraries. At Los Alamos, we generally recommend the use of data libraries derived from ENDF/B-V. Validation of data libraries is an extremely complex issue and is impossible to separate from validation of a transport code for a particular application. The transport code/data library user must also be knowledgeable.

It is often important to know how much energy is deposited in various regions of a device. This problem is typically modeled in radiation transport codes by folding the calculated fluences with an energy-dependent "heating number." The heating number represents the average energy deposited locally per collision. Calculation of these heating numbers from evaluated data libraries is fraught with difficulty. The often-used energy-balance method is prone to produce physically unrealistic heating numbers. The NJOY code incorporates a more rigorous calculation of heating, using the KERMA method. Many past difficulties related to energy deposition should be resolved by the release of ENDF/B-VI.

Outline

- Cold Neutron Source Data Needs
- Nuclear Data Evaluations / Processing / Libraries
 - Transport Data
 - KERMA's
- Validation / Verification
- ENDF/B-VI
- Library Availability

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

Cold Neutron Source Data Needs

- Coupled Neutron/Photon Transport Libraries
 - Neutron Interaction Data
 - Neutron-Induced Photon-Production Data
 - Photon Interaction Data
- Neutron Thermal $S(\alpha, \beta)$ Data
- Response Function Data
- Proton Interaction Data

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

Los Alamos

Data Libraries Are of Two Forms

- **Pointwise**
 - Cross sections are specified at a sufficient number of energy points to faithfully reproduce the evaluated cross section.
 - Used with:
 - Continuous energy Monte Carlo codes
- **Multigroup**
 - All data are collapsed and averaged into energy groups.
 - Used with:
 - Diffusion codes
 - Discrete Ordinates codes
 - Multigroup Monte Carlo codes

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

POINTWISE CROSS SECTION

03/03/91

ZAID = 26000.55C

Fe - NAT

From RMCCS

MT = 1

TOTAL

Los Alamos

03/03/91

ZAID = 26000.55M

Fe - NAT

From MENDF5

MT = 1

TOTAL

Los Alamos

Cross Section Libraries

- **Pointwise**
 - User does not have to worry about:
 - Group structure
 - Flux spectrum
 - Self-shielding
 - Small amount of work in processing code
 - Large amount of work in transport code
- **Multigroup**
 - User needs to worry about everything
 - Large amount of work in processing code
 - Small amount of work in transport code

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Evaluated Libraries/Processing Codes/Data Libraries

- **Evaluations**
 - ENDF/B-V (and earlier versions)
 - ENDL
 - JEF
 - JENDL
 - etc.
- **Processing Codes**
 - NJOY
 - AMPX
 - RECENT
 - etc.
- **Data Libraries**
 - pointwise
 - RMCCS
 - etc.
 - multigroup
 - MATXS
 - VITAMIN
 - ANSL
 - etc.

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Many Different Cross-Section Sets Are Available

- Different evaluations
- Different processing codes
- Different processing
 - resonance reconstruction
 - temperature
 - self-shielding
 - group structure
 - weight function

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

XSLIST - CROSS SECTION SELECTION

Z = 8 ***** OXYGEN *****

** 0-16 **

ZAID	FILE	SOURCE	MAT TYPE	TEMP	GPD	LENGTH
8016.01C	XMCCS	ENDL-73	514 CONT	0 YES	H*	5540
8016.02C	XMCCS	LAMDF	5514 CONT	0 YES	H*	4791
8016.04C	BMCCS	ENDF/B-IV	1276 CONT	0 YES	P	21823
8016.04D	D9	ENDF/B-IV	1276 DISC	0 YES	P	10486
8016.30C	AMCCS	ENDL-76	7114 CONT	0 YES	P	4565
8016.30D	D9	ENDL-76	7114 DISC	0 YES	P	4739
8016.50C	RMCCS	ENDF/B-V	1276 CONT	300 YES	P(E)	38003
8016.50D	DRMCCS	ENDF/B-V	1276 DISC	300 YES	P(E)	20516
8016.51C	ENDF5T	ENDF/B-V	1276 CONT	300 YES	P(E)	37996

What's a user to do?
Use defaults?
Choose the appropriate set?
How?

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

THINGS TO CONSIDER WHEN CHOOSING NEUTRON CROSS SECTION TABLES

- Differences in evaluator's philosophies
- Neutron energy spectrum
- Temperature at which set was processed
- Availability of photon-production data
- Sensitivity of results to different evaluations
- Use the best data that you can afford

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

Recommendation

- **At Los Alamos, we generally recommend the use of ENDF/B-V data, unless there is a specific reason not to, such as:**
 - **known disagreement with measured cross sections**
 - **energy-balance problems**
 - **no photon production**
- **This will likely change with the release of ENDF/B-VI.**

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

PHOTON INTERACTION CROSS SECTIONS

03/03/91
ZAID = 82000.01P
Pb
From MCPLIB

MT = 501
TOTAL

MT = 502
COHERENT

MT = 504
INCOHERENT

MT = 516
PAIR PRODUCTION

MT = 602
PHOTOELECTRIC

Thermal $S(\alpha, \beta)$ Libraries

- Representation of thermal neutron scattering by molecules and crystalline solids.
- Attempt to account for crystalline structure, molecular vibrational and rotational levels, as well as other detailed low-energy physics.
- Evaluated data can be processed into pointwise or multigroup format.

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

ZAID	Description	Isotopes	Temperature (K)
LWTR.01T	Light water	1001	300
LWTR.02T	Light water	1001	400
LWTR.03T	Light water	1001	500
LWTR.04T	Light water	1001	800
LWTR.05T	Light water	1001	800
POLY.01T	Polyethylene	1001	300
H/ZR.01T	H in ZrHx	1001	300
H/ZR.02T	H in ZrHx	1001	400
H/ZR.04T	H in ZrHx	1001	800
H/ZR.05T	H in ZrHx	1001	800
H/ZR.06T	H in ZrHx	1001	1200
BENZ.01T	Benzene	1001,6000,8012	300
BENZ.02T	Benzene	1001,6000,8012	400
BENZ.03T	Benzene	1001,6000,8012	500
BENZ.04T	Benzene	1001,6000,8012	800
BENZ.05T	Benzene	1001,6000,8012	800
HWTR.01T	Heavy water	1002	300
HWTR.02T	Heavy water	1002	400
HWTR.03T	Heavy water	1002	500
HWTR.04T	Heavy water	1002	800
HWTR.05T	Heavy water	1002	800
BE.01T	Beryllium metal	4009	300
BE.04T	Beryllium metal	4009	600
BE.05T	Beryllium metal	4009	800
BE.06T	Beryllium metal	4009	1200
BE0.01T	Beryllium oxide	4009,8016	300
BE0.04T	Beryllium oxide	4009,8016	600
BE0.05T	Beryllium oxide	4009,8016	800
BE0.06T	Beryllium oxide	4009,8016	1200
CRPH.01T	Graphite	8000,8012	300
CRPH.04T	Graphite	8000,8012	600
CRPH.05T	Graphite	8000,8012	800
CRPH.06T	Graphite	8000,8012	1200
CRPH.07T	Graphite	8000,8012	1800
CRPH.08T	Graphite	8000,8012	2000
ZR/H.01T	Zr in ZrHx	40000	300
ZR/H.02T	Zr in ZrHx	40000	400
ZR/H.04T	Zr in ZrHx	40000	800
Zr/H.05T	Zr in ZrHx	40000	800
Zr/H.06T	Zr in ZrHx	40000	1200

*Isotopes for which the S(α,β) data are valid

Newer S(α,β) Libraries for MCNP (from R.E.MacFarlane/LEAPR)

- HPARA.01T -- para hydrogen at 20 degrees Kelvin
- HORTHO.01T -- ortho hydrogen at 20 degrees Kelvin
- DPARA.01T -- para deuterium at 20 degrees Kelvin
- DORTHO.01T -- ortho deuterium at 20 degrees Kelvin
- SMETH.01T -- hydrogen in solid methane at 22 degrees Kelvin
- LMETH.01T -- hydrogen in liquid methane at 100 degrees Kelvin

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

"Response Function" Cross Sections

$$N * \phi(E) * R(E)$$

R(E) might be:

- **Activation cross section**
- **Gas production cross section**
- **Energy deposition (Heating, KERMA)**
- **Radiation damage response function**

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Energy Deposition (Heating)

- **Often need to know how much energy is deposited in various components of the system.**
- **For neutron and photon transport, if all secondary particles were produced and transported, then there would be no direct heating from the neutral particles.**
- **However, secondary charged particles and recoils are generally not produced and transported. Therefore, the kinetic energies of these particles is assumed to be deposited locally -- we will call this heating.**

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

NEUTRON ENERGY DEPOSITION

03/03/91

ZAID = 26000.55C

Fe -- NAT

From RMCCS

MT = 301

HEATING

Los Alamos

PHOTON ENERGY DEPOSITION

03/03/91

ZAID = 26000.01P

Fe

From MCPLIB

MT = 301

HEATING

Los Alamos

Calculation of Heating Direct Method

- The direct method to calculate heating for each reaction is to sum the energies of all secondary reaction products not transported. Then combine the reaction sums, weighting by the cross sections.
- Unfortunately, ENDF/B-V does not include the necessary information. Therefore, the direct method is not viable.

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Calculation of Heating Energy-Balance Method

- In the energy-balance method, the secondary neutron and photon energy is subtracted from the available energy.
$$H(E) = E + Q - E_n - E_\gamma$$
- The energy-balance method is used in NJOY for processing ENDF/B-V evaluations (except for radiative capture).
- There are problems with this method, resulting from:
 - sloppy or inconsistent evaluations
 - no energy-dependent Q-values for elemental evaluations
 - threshold effects
- These problems often have led to negative heating numbers, or unrealistically large positive ones.

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

EXAMPLE OF BAD ENERGY BALANCE

03/03/91

ZAID = 24000.50C

Cr - NAT

From RMCCS

MT = 301

HEATING

Calculation of Heating KERMA

- KERMA - Kinetic Energy Release in Materials
- NJOY calculates KERMA from
 - conservation of momentum
 - kinematic limits
- The upper kinematic limit is used, giving a conservative (maximum) value of heating.

Los Alamos

RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION

Incorrect Energy Deposition

- If an evaluation produces obviously incorrect values for energy deposition, two things can be done:
 - Replace heating values with reasonable numbers
c.g., KAOS/LIB-V
 - Re-evaluate the data set

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

ENDF/B-VI Major New Features

- Incident charged-particle evaluations
- Charged-particle spectra from neutron interactions
- Correlated energy-angle distributions
- Incident energy range extended to 100 MeV
- Reich-Moore R-matrix resonance parameters
- Unlimited distribution

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

ENDF/B-VI Important New or Updated Evaluations

- Most of the important light element, structural, fissile, and fertile material evaluations have been extensively revised.
- Isotopic evaluations for major structural materials are now available.
- Simultaneous re-evaluation of neutron standard cross sections, plus Pu-239, U-238, and U-235 fission cross sections.
- Extension of resolved resonance region for U-235, U-238, and Pu-239 to higher energies.

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

ENDF/B-VI Implications for Heating Values

- Evaluators are encouraged to include secondary energy-angle distributions for all of the emitted particles:
 - secondary neutrons and photons
 - secondary charged particles
 - recoil nucleus
- If evaluators do include such data, processing codes can use the direct method to calculate heating (instead of the energy-balance method).
- This should lead to large improvement in the accuracy of calculated heating values, as well as improvement in the accuracy of other calculated quantities, such as damage.

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Validation / Verification Studies

- CSEWG Data Testing
 - Phase I - compare experimental and evaluated cross sections
 - Phase II - calculate benchmark experiments (ENDF-311)
- Processing Code Benchmarking / Testing
 - IAEA effort turned up many errors
- Transport Code Benchmarking
 - Diffusion vs. S_N vs. Monte Carlo

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Validation Summary

- **All testing and benchmarking of data, processing codes, and transport codes is helpful.**
- **Ultimately, however, it must be the responsibility of a particular user community to validate data and codes for its particular applications.**
- **Remember that data evaluations, processing codes, and transport codes have been supported by certain programs and developed for certain applications. One must be careful when one strays far away from the originally intended applications.**

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Examples of Valuable References

- **R. Kinsey, compiler, "ENDF/B Summary Documentation," Brookhaven National Laboratory report BNL-NCS-17541 (ENDF-201) 3rd edition (ENDF/B-V) (July 1979).**
- **H. M. Fisher, "A Nuclear Cross Section Data Handbook," Los Alamos National Laboratory report LA-11711-M (December 1989).**

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Availability of Cross-Section Libraries

- We distribute our codes and data libraries primarily through the:
 - Radiation Shielding Information Center (RSIC) at Oak Ridge
- Other centers where we attempt to maintain our codes and data include:
 - NMFECC - Magnetic Fusion Energy Center at Livermore
 - NESC - National Energy Software Center at Argonne
 - SDSC - San Diego Supercomputer Center
- As a general rule, we cannot afford to distribute codes and data libraries directly.

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Availability of Pointwise Cross-Section Libraries

- All cross-section libraries currently available at Los Alamos are also available at RSIC as part of the MCNP code package.
 - Default libraries are based on ENDF/B-V; therefore unavailable for foreign distribution.
 - Alternative libraries are available - e.g., ENDL-85, ENDF/B-IV, etc.
- We do not have the absolute latest thermal $S(\alpha, \beta)$ libraries from Bob MacFarlane. When we do, we will also distribute these libraries through RSIC.

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Availability of Multigroup Cross-Section Libraries

- **Examples of standard MATXS multigroup libraries from Los Alamos:**
 - 30 X 12 set - useful for many benchmark, fusion, and shielding problems.
 - 69 X 24 set - thermal reactor problems.
 - 187 X 24 set - accurate thermal reactor, fast reactor, fusion, and shielding calculations.
- **Current libraries at RSIC are relatively old, and will probably be updated this year.**
- **These multigroup sets are based on ENDF/B-V; therefore unavailable for foreign distribution.**

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Availability of ENDF/B-VI

- **Evaluated libraries are becoming available now. Should be completely available by summer.**
- **Processing and transport codes need to be enhanced to handle new ENDF-6 formats.**
- **Actual processing, testing, and distribution of libraries based on ENDF/B-VI will be a significant job.**
- **Unrealistic to expect general-purpose pointwise or multigroup libraries based on ENDF/B-VI from Los Alamos during this year.**

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Summary

- Cold Neutron Source studies require a variety of nuclear and atomic data.
- A large number of evaluated libraries, processing codes, data libraries, and transport codes are available.
- Los Alamos generally recommends the use of data based on ENDF/B-V.
- There are significant problems with heating values from certain evaluations. ENDF/B-VI will alleviate some of the difficulties.
- Data and codes have been extensively benchmarked. Ultimately, however, a particular user community must validate data and codes for use in relevant applications.
- New thermal $S(\alpha,\beta)$ libraries and libraries based on ENDF/B-VI will be made available at the earliest feasible date.

Los Alamos

**RADIATION TRANSPORT GROUP
APPLIED THEORETICAL PHYSICS DIVISION**

Cross Section Libraries and Kerma Factors

Robert C. Little

Questions/Answers/Comments

(R. Lillie)

Question:

Why will transport codes need to be modified to be able to use ENDF/B-VI data?

Answer:

Several enhancements in format require changes in Monte Carlo codes. For example, correlated energy-angle distributions are now allowed in ENDF/B-VI; they were not in previous versions. Energy-dependent multiplicities are now allowed for reactions other than fission. Particle-production spectra (for example, protons, alphas, etc.) are now specified in ENDF/B-VI from neutron reactions. If we truly want to generalize our codes from neutron-photon to n-particle, using these spectra will be a significant component. This last point also applies to multigroup libraries and codes. In all cases, there will be significant new capabilities required of processing codes.

(R. Lillie)

Question:

Some of the new ENDF/B-VI reaction-product data involve delayed data. Will this be handled in the transport codes?

Answer:

I believe that the ENDF/B-VI format allows for complete specification of delayed data. Processing codes such as NJOY have been able to process neutron/photon data using prompt or steady-state assumptions. I assume the same will be true for calculating heating from prompt/delayed secondary particles in ENDF/B-VI. MCNP currently has a data base that is primarily oriented for prompt problems, for example, delayed photons from fissions are not included. We hope to soon be able to work on improved, delayed data, and algorithms.

(E. Lynn)

Comment:

I would like to reiterate the points you made about user awareness of the background of the data base and also to stress the importance of continued maintenance and extension of data bases. One particular horror story I remember from several years ago in the U.K. was the discovery that in a much used data base, where cross-section values were unknown, zeros had simply been inserted, regardless of the likely physical magnitudes of those quantities. This could, of course, have led to serious problems if the use of the data base had been extended to uses not intended by its origination.

(R. Little)

Comment:

I agree that it is important to not use data sets outside the intended area of applicability. The most visible case for CNS community has been $S(\alpha, \beta)$ kernels. There may be other, less visible problems lurking beneath the surface.

Monte Carlo Calculations for the CRNL Cold Neutron Source Design

Peter M. Brewster

Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories
Chalk River Ontario, Canada, KOJ 1J0

ABSTRACT

The MCNP code and neutron-scattering kernel data for the liquid hydrogens are used in preliminary calculations to compare the conceptual designs of cold neutron source chambers for the NRU reactor. The relative flux of neutrons, as a function of energy, directed into beam tubes is predicted. Results comparing a multifaceted reentrant shape with a simple convex shape are obtained. Care is needed to extract a reliable estimate of the experimental cold neutron advantage factor from the simulations.

I. INTRODUCTION

Neutrons of energy less than 0.005 eV are commonly called cold neutrons. A cold neutron source is being designed for installation in the third vessel of the NRU (National Research Universal) reactor at Chalk River Nuclear Laboratories. This report describes the method used to calculate the flux in the beam tubes to assist in the design of the cryogenic chamber.

Goal

This preliminary study is needed to confirm the suitability of the MCNP (Monte Carlo Neutron Photon) code as an aid to optimizing the design of the cold neutron

source chamber. Calculation of the yield of cold neutrons from the different designs provides a quantitative evaluation of the major issues:

- comparison of H₂ with D₂,
- evaluation of the effect of ortho and para molecular spin states,
- optimization of chamber volume and shape.

A product of this study is the prediction of the enhancement of the cold neutron flux which can be obtained in the NRU reactor. The gain, or advantage factor, is defined as the ratio of the neutron current in the experimental beam, with the 20 K cold-source present, to the current with a 314 K heavy-water scattering can present. The direct estimate of this quantity is the calculated gain, as a function of neutron energy:

$$\text{Gain} = \frac{\text{Flux exiting the beam tube with CNS present}}{\text{Flux exiting the beam tube with the Ref-can of D}_2\text{O}}$$

Numerous mistakes in setting up the problem have been identified, and improvements will be incorporated in the next set of calculations.

Conceptual Designs

The cold source for NRU is described in more detail in another paper in these proceedings [1]. The design of the third vessel for NRU includes a unique arrangement of beam tubes to serve three spectrometers, Fig. 1. The large T3 tube contains the cold-source chamber inside a strong vacuum can, which will also function as a beam port. At right angles, the C2/N2 through-tube intersects the end of the T3 tube, forming a Tee. All of these tubes have oval cross sections and are made of an aluminum alloy. The NRU reactor is D₂O cooled and moderated. The reactor has a heterogeneous loading, including about 100 fuelled assemblies dispersed in the lattice of 227 sites on a hexagonal pitch of 0.197 m. The vertical fuel rods of length 2.7 m are located on all sides of the Tee tubes.

The beam-tube axes are at the central elevation and the T3 leg blocks 7 reactor positions.

With the dimensions of the beam tubes specified by the vessel design, the main cold-source options are the selection of the cold scattering material and optimization of the size and shape of the chamber. Liquid deuterium (D_2) and liquid protium (H_2), at 20 K, are the two preferred materials. The chamber concepts to be compared are liquid D_2 in an oval can of the maximum practical volume, and liquid H_2 , in a variety of shapes which present hydrogen thicknesses of a few centimetres to the field of view of the three beam tubes. It is also necessary to specify the time-averaged ortho to para ratio of the molecular states, and the net density consistent with the vapourization rate in the chamber.

II. SIMULATION PROBLEM

The MCNP code was selected for this study [2]. This code simulates neutron transport with few assumptions [3]. Neutron scattering in H_2 and D_2 is treated using neutron-scattering kernels developed by MacFarlane [4]. Another strength of MCNP is its capability of exact three-dimensional geometrical modelling, which allows evaluation of the effect of changes in the shape of the chamber. An expected benefit will be the use of the optimized geometrical model to evaluate the nuclear heat load with MCNP.

Cold-Source Chamber Concepts

Figure 1 shows the three chamber concepts. The Oval-can contains ortho deuterium (o- D_2). The Slab chamber is modeled full of para H_2 (p- H_2) and again with ortho H_2 (o- H_2) in order to indicate the magnitude of the effect of molecular state. The simple slab placed diagonally in the vacuum tube minimizes the hydrogen inventory and minimizes the heat load. The Cross chamber concept has concave surfaces facing the beam tubes. The Cross provides the same thickness of H_2 (in the C2/N2 direction) as the Slab and also has top and bottom 'reflector' regions, which intersect more neutron paths. The Cross chamber is modeled with o- H_2 for comparison with the Slab of o- H_2 , in order to quantify the effect of chamber shape on the yield of cold neutrons.

The volumes and masses of structural material are summarized in Table I. The intersecting oval beam tubes are modelled exactly, aided by the use of the SABRINA code [5]. All chambers are modelled with solid aluminum walls 3.2 mm

thick. The normal liquid densities at 20 K are used, and no void fraction is included. The vacuum can is modelled with solid walls 6.35 mm thick. Supply and return lines for liquid hydrogen are omitted.

The Oval chamber extends 35 mm beyond each side of the C2/N2 through-tube opening, and is the largest practical volume for the Tee-tube arrangement. The inside dimensions are 146 mm in the T3 direction, 254 mm high and 140 mm in the C2/N2 direction. The same chamber, inside the vacuum can, is used for a heavy-water reference (Ref-can), which is simulated as the standard to quantify the enhancement of the cold neutron yields.

Fig. 1. View of the NRU beam tubes and cold-source chambers

TABLE I
SUMMARY OF INITIAL CHAMBER DESIGNS

No.	Chamber	Contents		mass [g]	volume [L]	Structural Wall Mass of Aluminum [kg]
		temperature [K]	molecule			
1	Oval	20	o-D ₂	640	4.6	1.4
2	Slab	20	p-H ₂	66	0.95	0.84
3	Slab	20	o-H ₂	66	0.95	0.84
4	Cross	20	o-H ₂	76	1.10	1.1
5	Ref.	314	D ₂ O	5028	4.6	1.4

Both the Slab and Cross chamber models have liquid hydrogen thicknesses of 40 mm across the field of view of the C2/N2 beam tubes, although the total volumes and the thicknesses in the T3 direction are different. The Slab chamber has a projection in the T3 direction of 33 mm and a trapezoidal horizontal section 25 mm thick. The volume is 0.95 litres.

In the Cross chamber, two crossed slabs plus a central box provide a constant 40 mm projection in the C2/N2 direction. The total projected thickness in the T3 direction is 29.5 mm, except in the nonuniform central region. In addition, there are annular caps of 20 mm thickness at the top and bottom (beyond the central 200 mm height). The "Cross" region has a volume of 0.75 litres and each cap has a volume of 0.17 litres. Internal walls in the oval chamber separate displacer regions, which fill with H₂ vapour from the cross-shaped liquid region. The internal walls are omitted from the model, and vacuum is used as the displacer material.

Options

The inside of the beam tubes end at MCNP 'tally planes', at a distance of 0.305 m from the origin, as shown in Fig. 2. In NRU, collimators limit the field of view of the beams to about 1 degree, 6 m from the chamber. This is too restrictive for analog Monte Carlo calculations. Two methods are used to estimate the flux directed down the beam tubes: i) neutrons which pass into the chamber at some time in their history before reaching a tally plane are flagged, and ii) neutron paths which make an angle of less than 20 degrees with the outward surface normal

are placed in separate tallies. Note that the attractive MCNP options of point detectors and DXTRAN (deterministic transport to a spherical region, i.e., around the chamber), are not available with the S(alpha,beta) thermal-scattering treatment.

Fig. 2. Section of the reactor and cold-source for MCNP calculations

Scattering kernel data for 20 K o-D₂, p-H₂, o-H₂ [4], and 300 K D₂O [2] are used with ENDF/B-4 data files [2].

Cell average fluxes are also tabulated for the cold chamber and heavy-water cells at the inward end of the T3 tube, and in the moderator far from the beam tubes.

All output tallies are divided into 21 energy bins. The bin boundaries in millielectron volts are :

0.0	0.422	0.562	0.75	1.	1.33	1.78	2.37	3.16	4.22	5.62
7.5	10.0	13.3	17.8	23.7	31.6	56.2	100.	178.	316.	562.

Neutron Source

The NRU reactor is assumed to provide a Maxwellian distribution of neutrons at a temperature of 314 K. Epithermal and fast neutrons are ignored in this preliminary study. All neutrons are started from a radius of 0.24 m, and are inwardly directed with a cosine distribution. Neutrons are not started from any point on the source sphere with coordinates within 10 mm of any of the beam tubes. This is done by means of an MCNP cookie-cutter rejection cell and prevents neutrons from starting in the beam tubes. This source results in a non-isotropic thermal neutron distribution, which is considered to be reasonable, since the NRU reactor has similar flux gradients. The heavy-water moderator is limited to a sphere of 0.6 m diameter. This is assumed to be big enough to see the interaction of the cold-source with the neutron spectrum from the surrounding heavy water. This small source diameter delivers neutrons efficiently to the chamber, but only approximates the true input spectrum. The MCNP runs all use the same neutron-source strength, which is a reasonable means of normalization.

Variance Reduction

Two standard Monte Carlo techniques are used to reduce the uncertainty of the output quantities. The analog capture option is recommended for tracking thermal neutrons in weakly absorbing materials [3]. Geometrical importance splitting is used to increase the number of tracks entering the cold chamber. An importance of 2 is specified for the walls of the vacuum can and the beam tubes, and for heavy water in a rectangular box within 20 mm of the Tee-region beam tubes. An importance of 4 is specified for the chamber walls and contents.

III. RESULTS AND DISCUSSION

The MCNP ledger table for 10^6 source neutrons (Cross o-H₂ case) shows that a further 2×10^6 tracks are created by cell importance, and 1.8×10^6 tracks are terminated by roulette, upon entering less important cells. This represents 2/3 of the neutrons created. We have not verified the suitability of this degree of splitting.

A time cutoff of 1 ms is imposed, and terminates neutrons representing 0.15% of the neutron weight (0.4% of the weight in the chamber). The time cutoff option is intended to kill neutrons which 'rattle' around interminably in the heavy water. Unfortunately, the time cutoff discriminates against cold neutrons, and has biased the present results. The time cutoff option will not be used in future neutron-gain calculations.

Neutron capture terminates 0.8% of the neutron weight. The ortho hydrogen accounts for 18% of all the captures in the problem.

The cookie cutter around the beam tubes rejects 26% of the initial source neutrons.

Fig. 3.

Comparison of the room-temperature spectra with a Maxwellian distribution shows the hardening due to $1/v$ absorption in the aluminum.

Figure 3 is a plot of the cell-average flux spectrum in the CNS chambers and the heavy-water reference can. The energy range from 1.78 to 23.7 meV is shown. On the plots, lines are drawn to connect the bin midpoints, instead of using histograms. The two o-H₂-filled chambers display very similar spectral shapes, although the flux in the Slab is 15% greater than in the Cross at the low-energy end. The statistical uncertainty is better than 1% (one standard deviation) except for the Ref.-can flux.

Figure 4 shows the fluxes at the T3 beam-tube tally plane flagged by the chamber cell. There is no discrimination of neutron direction in this tally. At 5 meV a cold neutron gain factor of 4 is indicated, relative to the D₂O case, for all four chambers modelled.

Chamber-flagged spectrum at the T3 beam tube tally plane

Preliminary comparison of conceptual designs for cold-source chambers

Fig. 4.

Sum of the chamber-flagged spectra at the C2 plus N2 beam tube tally planes

Preliminary comparison of conceptual designs for cold-source chambers

Fig. 5.

Figure 5 displays the chamber-flagged tally summed over the C2 and N2 tally planes. The Oval can of o-D₂ and the p-H₂ Slab indicate the greatest yield of neutrons between 5 and 10 meV, which is not the result expected. This indicates that the deuterium chamber should be retained in the optimization study. The uncertainty is 5% at 5 meV (11% for the D₂O Ref.-can calculation).

Figure 6 shows the neutron current at the T3 tally plane for neutrons making an angle of 20 degrees or less with the axis (without the chamber-flagging option). This angle intersects the complete chamber and a considerable fraction of the heavy water. The results in Figs. 4 and 6 are inconsistent in some details. The o-D₂ can fares better in the chamber-flagged tally than in the direction tally, demonstrating the need for a single, reliable estimator.

Fig. 6.

Fig. 7.

Figure 7 shows the spectra of neutrons reaching the C2 and N2 tally planes within 20 degrees of the through-tube axis. The uncertainty is $\pm 5\%$ in the bin at 5 meV (11% for the Ref-can).

No firm preference for the chamber design should be drawn from these flawed, preliminary calculations.

IV. CONCLUSIONS

The combination of exact geometric modelling and correct scattering treatment make MCNP a very powerful computational tool. The MCNP code is capable of simulating the performance of cold sources with various moderators and differing shapes. Care is needed to include the essential features without needlessly increasing the cost of the computation.

The position of the tally plane adjacent to the heavy-water moderator results in a large, direct contribution to the flux in the beam tube (much larger than in a well-collimated experimental beam tube). The contribution depends on neutron energy, and on which cold-source chamber is in place, biasing the desired spectrum. Moving the tally planes 0.3 m further from the chamber will reduce the "signal" from the chamber by reducing the solid angle, but will also reduce the "noise" from the heavy water by a much greater factor. Additional angular tally bins of 3, 6, and 10 degrees to the axes will permit comparisons of beam currents summing a wide energy range at the 3 degree acceptance angle, as well as a single energy bin over the whole field of view. It is recommended that angular bin and chamber-flagging tallies be applied simultaneously to improve the simulation of the experimental beams.

Low-energy neutrons from the heavy water have a greater effect on the small, 314 K reference tally than on the larger, cold-source tallies. The neutron-gain ratios are therefore lower bound estimates of the true advantage factors which would be obtained.

Some general conclusions can be drawn:

- The available volume is sufficient to continue consideration of liquid deuterium, in the quest for the maximum yield of cold neutrons.
- Comparing the two o-H₂ sources indicates that the reentrant Cross shape yields somewhat more cold neutrons than the convex Slab. Further optimization will be needed to determine if the advantage is worthwhile.
- The effect of the ortho to para ratio in H₂ appears to be greater than the shape effect.

V. FUTURE PLANS

Another series of calculations will be performed. The tally planes will be moved out to 0.6 m from the chamber. More restrictive tally conditions will be imposed to reduce the effect of uncollimated neutrons. A realistic distribution of epithermal source neutrons will be included in the reactor source description. Realistic time-averaged ortho to para ratios will be used for the S(alpha,beta)

thermal-scattering data, combined with ENDFB/5 data files. The liquid hydrogen density will be reduced 20% to account for boiling.

Optimization of each of the three chamber concepts is important, to identify the best design unambiguously and to understand the tradeoffs. In the next calculations, the Oval-can may be filled with an isotopic mixture of 10 atom% protium in deuterium to increase the number of collisions. The thickness of the Slab chamber and the Cross chamber arms may be reduced to 30 mm, parallel to the C2/N2 axis. Ultimately, the selected design will take into account the heat load as well as the cold neutron yield.

VI. ACKNOWLEDGEMENTS

Thanks are due to Bob MacFarlane and LANL for providing the scattering kernels. Many people at AECL have contributed to the development of the NRU cold-source project-- in particular, Bill Buyers, Varley Sears, and Eric Svensson. The MCNP geometry files were meticulously prepared by Gwen Campbell, a summer student employee.

VII. REFERENCES

1. E.C. Svensson, V.F. Sears, P.M. Brewster, W.J.L. Buyers, W. Mellors, "The Cold-Source for the NRU Reactor at Chalk River", International Workshop on Cold Neutron Sources, Los Alamos, 1990 March 5-8, (this workshop).
2. The Monte Carlo Neutron and Photon Transport Code System, MCNP 3B, available from the RSIC Computer Code Collection, Radiation Shielding Information Centre, Oak Ridge National Laboratory.
3. "MCNP-A General Monte Carlo Code for Neutron and Photon Transport, Version 3A", J. Briesmeister, Ed., Los Alamos National Laboratory Report LA-7396-M (1986 September) and "MCNP3B Newsletter", J. Briesmeister, Ed., Los Alamos National Laboratory (1988 July 18).
4. R.E. MacFarlane, "Cold Moderator Scattering Kernels", ICANS-X Proc. of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources, Los Alamos, 1988 October 3-7, D.K. Hyer, Ed.
5. J.T. West, "SABRINA: An Interactive Three-Dimensional Geometry-Modeling Program for MCNP", Los Alamos National Laboratory Report LA-10688-M (1986 October), and available from RSIC, Oak Ridge National Laboratory.

Monte Carlo Calculations for the CRNL Cold Neutron Source Design

Peter M. Brewster

Questions/Answers/Comments

(W. Bernnat)

Question:

How large were the statistical errors of your results and how did you choose your energy bins?

Answer:

Eight energy bins per decade were used, starting at 0.42 meV, and exponential spacing in the range below 20 meV. More bins will be used in future calculations, for almost no additional computing cost.

The statistical uncertainty of the beam tube tallies was generally 5% for the bin at 5 meV. A relative error of 10% is considered to be a reliable estimate.

(A. Lee)

Question:

It would be very useful to perform adjoint flux calculations for beam-tube performance using the Monte Carlo Neutron Photon Transport Code and point-wise continuous data libraries. Is this possible?

Answer:

(B. Little) Currently, the Monte Carlo Neutron Photon Transport Code can do adjoint calculations for multigroup cross-section problems. While we would like to do continuous-energy adjoint, the chances of this are very small in the near future.

(P. Brewster)

Comment:

Additional insight into the physics is obtained by examining the number of collisions occurring in each chamber and the total neutron population in each chamber, without regard for energy or direction. The results of the Monte Carlo Neutron Photon Transport Code calculations are:

Chamber	Moderator	Collisions [10 ⁶]	Population [10 ⁶]	Ratio
Oval	o-D ₂	3.1	1.5	2.1
Slab	p-H ₂	0.8	0.7	1.1
Slab	o-H ₂	5.0	0.7	7.2
Cross	o-H ₂	6.3	0.9	6.8
Ref	D ₂ O	0.8	1.6	0.5

Relative to the Slab, the population of neutrons reaching the Cross is only slightly greater than the volume increase of 15%. On the average, the para-H₂ Slab acts as a single scatterer and the large D₂ Oval chamber as a double scatterer. About seven collisions per neutron occur in the two chambers filled with ortho-H₂.

Session III

COLD SOURCE DESIGN CONSIDERATIONS (Part I)

Chairman

Bernard Farnoux

Some Remarks on Design Criteria and Optimization Concerns for Cold Neutron Sources

G.S. Bauer

PAUL SCHERRER INSTITUTE

CH 5232 Villigen-PSI, Switzerland

1 INTRODUCTION

When speaking about "cold neutron sources" one actually refers to a low temperature moderator on a neutron source. A true source of cold neutrons, i.e. where neutrons are in the meV range when set free from nuclear matter, is not possible to design. This distinction, although it might appear purely semantic at a first glance, is important in understanding what options exist in making cold neutrons available to suit experimental needs. The important point is, that cold neutrons are generated by transporting neutrons from higher to lower energies. In principle, this can be done by either a coherent transformation, i.e. all neutrons suffer the same fate in a collective way like in a Bragg reflection, or by incoherent transformation, where each neutron is acted upon individually, independent of all others. In the first case Liouville's theorem applies, which means that the density in phase space remains constant. In the second case the phase space is filled anew and its density is increased according to the lower moderator temperature. Hence, only the incoherent transformation is of interest, if high intensity cold neutron beams are to be provided from neutrons at higher energies.

2 PHASE SPACE DENSITY AND OPTIMIZATION OF NEUTRON EXTRACTION FROM FINITE SIZE MODERATORS

Generally the neutron flux is given as the product of neutron density and neutron velocity

$$\phi(v) = v \cdot \frac{d^3 N(v)}{dx dy dz} \quad (1)$$

For neutrons in thermal equilibrium with an ideal moderator at temperature T , the energy distribution has the form of a Maxwellian:

$$\phi(E) = \phi_{th} \cdot \frac{E}{E_T^2} \cdot \exp(-E/E_T) \quad (2)$$

where ϕ_{th} is the total thermal neutron flux and $E_T = k_B \cdot T$ is the energy corresponding to the moderator temperature T .

Introducing the neutron wave number k , one has

$$k = \frac{1}{\hbar} \sqrt{2 m E} = 2\pi/\lambda \quad (3)$$

and the phase space density

$$\frac{d^6 N}{dx dy dz dk_x dk_y dk_z} = \frac{\phi}{\pi} \cdot \frac{m}{\hbar} \frac{1}{k_T^4} \exp(-k^2/k_T^2) \quad (4)$$

with

$$k_T = (1/\hbar) \sqrt{2 m k_B \cdot T} \quad (5)$$

Equation (4) gives the phase space density inside a large moderator in thermal equilibrium. It is shown in Fig. 1 for three different moderator temperatures, namely 350 K, 50 K and 35 K. The enormous gain for small k -values by going to low temperature moderators is obvious.

In practice cold moderators are far from being ideal and are limited in size with an influx of thermal and hot neutrons through the surface and an outward leakage of cold neutrons. As a consequence the cold neutron flux distribution inside a cold moderator shows a strong spatial variation (buckling). This is exemplified in Fig. 2 which shows the calculated distribution of cold neutrons along the centre line of a liquid D_2 moderator embedded in a thermal D_2O moderator. The upper curve refers to the case, where the whole cold moderator is filled with liquid deuterium. It can be seen that the cold flux in the centre is about 2.5 times higher than the mean value between the two surface fluxes. (The difference between the two surface fluxes at the left and right hand side reflects the thermal flux gradient in which the moderator is located and the effect of the extraction void to the right). The three other curves shown give the flux distributions for the case where reentrant cavities are introduced to view the higher flux level inside the moderator. As can be seen from the flux levels at the respective inflection points a theoretical gain of the

order of 1.5 to 1.7 is possible relative to neutron extraction from the surface. In practice this gain may be reduced somewhat by absorption and extra heating due to the material introduced by the cavity, but this option deserves detailed consideration when ever large volume cold moderators are to be optimized.

Neutrons are transported from the cold moderator to the scattering experiments either through simple non-reflecting beam holes or via totally reflecting neutron guides. It is worth while considering the difference between the two, especially for long wavelengths (small k -values).

Beam hole

On a standard beam hole the cross section of the moderator surface illuminating the beam hole is constant for all neutron energies and so is the solid angle.

Hence we have

$$dx, dy = \text{const.}, x \cdot y = F_B \quad (6)$$

$$d\Omega = \frac{dk_x \cdot dk_y}{k^2} = \text{const.}, \Omega = \int d\Omega \quad (7)$$

and

$$dz = v \cdot dt = \frac{\hbar k}{m} dt \quad (8)$$

Introducing (6), (7) and (8) in (4), we obtain for the neutron current per unit area, unit solid angle, unit time and unit wave number:

$$j_B = \frac{d^6 N}{dx dy dt d\Omega dk_z} = \frac{\phi}{\pi} \cdot \frac{k^3}{k_T^4} \exp(-k^2/k_T^2) \quad (9)$$

The integration can be carried out immediately to yield:

$$J_B = \frac{d^2 N}{dt dk_z} = \frac{\phi}{\pi} \cdot F_B \cdot \Omega \frac{k^3}{k_T^4} \exp(-k^2/k_T^2)$$

Neutron guides

For the case of a neutron guide the transverse momentum that can be transported is constant for all k_z , i.e.:

$$dk_x, dk_y = \text{const.}, \Delta k_x = k_{Ni} = \Delta k_y \text{ for a nickel guide.} \quad (10)$$

Using (10), (6) and (8) with F_G being the cross section area of the neutron guide, one obtains from equ. (4):

$$j_G = \frac{d^6 N}{dx dy dt dk_x dk_y dk_z} = \frac{\phi}{\pi} \cdot \frac{k}{k_T^4} \exp(-k^2/k_T^2) \quad (11)$$

For a guide with all channel walls coated with nickel, one has

$$J_G = \frac{d^2 N}{dt dk_z} = \frac{\phi}{\pi} \cdot F_G \cdot k_{Ni}^2 \cdot \frac{k}{k_T^4} \exp(-k^2/k_T^2)$$

The distribution function given by equ. (11) is shown in Fig. 3 for different moderator temperatures.

It is obvious from equs. (9) and (11) that for small k -values (long wavelengths) extraction via a neutron guide is to be preferred and that the neutron guide should be brought up to the cold moderator as close as possible in order to exploit the full k_{Ni} , which is proportional to λ , also for long wave lengths. This, again, may conflict with heating problems and other needs, such as providing beam shutters, filters etc.

3 USES OF NEUTRONS FROM COLD MODERATORS AND RELATED OPTIMIZATION CONCERNS

The statement, that the planned use of the cold neutrons should be the prime concern in all optimization considerations seems trivial at a first glance. In practice, however, this has many facets. Of course, very often certain boundary conditions are fixed already, such as the type and operating characteristics of the primary neutron source. The situation is particularly complicated due to the fact that, very often, one cold moderator should serve several instruments which might pose different requirements. To illustrate this point, some typical examples of instruments with special features are given in the following. The list is by no means exhaustive but the examples may serve to illustrate some of the problems that arise.

3.1 INVERTED TIME-OF-FLIGHT SPECTROSCOPY ON A SHORT PULSED NEUTRON SOURCE (SPNS)

Apart from using long wavelength neutrons in their own right to examine low momentum transfer scattering, as dealt with in section 3.2, an important reason for building cold moderators on neutron sources with very short pulses of primary neutrons is to keep the neutron pulse short also in the thermal energy range by extending the slowing-down regime of a moderator to lower energies and thus avoid or reduce the need of poisoning the moderator.

The effect of poisoning, i.e. adding absorbing material with a certain outoff-energy at a depth of the order of 1 cm below the moderator surface is that neutrons with energies below the outoff can only emerge from the small surface layer. Thus long pulse tails are avoided, which could result from slow neutrons diffusing out from greater moderator depths.

Since, in the slowing-down regime, the neutrons are continuously removed from any given energy bin by collisions with the moderator atoms, the time between two collisions, and hence the life time τ of a neutron in any given energy bin is inversely proportional to the

neutron velocity at this energy or, in other words, $v \cdot \tau = \text{const.}$ Thus, in the slowing down regime, a moderator with high collision density and high energy loss per collision leads to intrinsically short pulses.

This is of relevance for all neutron sources delivering their fast neutron spectra in pulses with a duration of the order of one microsecond or less. Here the aim is to use flight time to determine the neutron energy incident on a sample and to do so over a wide energy range with good resolution. The pulse from the moderator is often used as the primary resolution element and hence the pulse should be well known in shape and duration as well as in its energy-dependent intensity.

There has been an ongoing discussion, whether the high emphasis placed on the pulse duration τ by the figure of merit

$$G = \frac{\int_{\text{pulse}} i(E, t) dt}{\tau^2} \quad (12)$$

given by Michaudon /2/ is justified or not, but there is general agreement that the exponent of τ should be at least 1, perhaps 1.5. This means that, while the total intensity delivered during a pulse is of importance, so is the shortness of the pulse. This in turn requires very short times between collisions i.e., high material density and high scattering cross section as well as high logarithmic energy decrement per collision down to low energies.

The requirement to have a very short pulse as such may perhaps be somewhat relaxed, if modern techniques such as the maximum entropy method can be used for data analysis /3/. As was shown by computer simulation /4/, deconvolution of a "contaminated" response function with a Gaussian and half-Gaussian of the same width τ (i.e. the same figure of merit according to equ. (12)) gives much better results for the half-Gaussian with a sharp leading edge.

This example, more than any other shows how important it is to be aware of the kind of use that is to be made of the neutrons from a cold moderator when contemplating its design and optimization criteria. The question "to poison, or not to poison" can be viewed in a new light under this findings, adding new significance to the argument about intensity losses in poisoned moderators, versus an integrated concept of data acquisition and processing.

The choice moderator material for cold moderators on an SPNS would

- have high hydrogen density, i.e. high slowing-down density
- have many degrees of freedom down to very low temperatures to enable energy transfer in the collisions
- have good heat removal properties at low temperatures and
- be resistant to radiation damage up to high doses.

This combination of properties is difficult to find on any substance. Candidate materials are discussed extensively in other papers of this workshop and will not be treated here in

any more detail.

In SPNS it is generally not easy to obtain good energy-dependent intensity monitoring on a pulse-to-pulse basis in the incident beam. Therefore moderator temperature stability within a few degrees is desirable to ensure reproducible spectral intensity distribution.

3.2 SCATTERING AT SMALL MOMENTUM TRANSFER

Many experiments require low incident energies to get the necessary resolution at very small Q-values. Depending on the type of experiment done, the ratio of scattered intensity to incident intensity may increase with the wavelength used, up to a λ^2 -behaviour found in many small angle scattering experiments. This can be true for neutron sources with or without time structure.

If the neutron source has no time structure to start with, the concern in cold moderator design is twofold:

- re-thermalization of the ambient thermal neutron flux with as little losses as possible
- efficient extraction of long wavelength neutrons

The problem of extracting cold neutrons from a limited moderator volume has already been touched upon in chapter 2. In addition to the points mentioned there, it is worthwhile to bear in mind another hindrance that should be minimized:

Any warm moderating material or absorbing material the cold neutrons have to cross on their path to the monochromator or sample will tend to remove cold neutrons from the beam either by absorption which is proportional to λ or by upscattering.

This latter effect has been calculated for different layer thicknesses of D_2O for the case of the SINQ cold source (Fig. 4).

The data in Fig. 4 pertain to two body scattering events in the D_2O layer. The apparent "recovery" at long wavelength is in this approximation due to a decrease in the D_2O cross section. In practice it is likely, however, that the approximation is not valid at long wavelengths and the curves stay down. Similarly, absorption in windows, which is not included in these calculations, would tend to reduce the long wavelength transmission.

In order to avoid this effect, the SINQ cold source will be placed in a T-shaped tube structure which allows to view the cold source directly without any layer of D_2O (Fig. 5).

Of course, the risk of upscattering by material in the beam path is the higher, the better this material is suited as a moderator. Graphite and Beryllium, too, are relatively good moderators, so one might be careful about the number of deflecting crystals of these

materials one puts in front a location, where long wavelength neutrons are to be used!

Also shown on Fig. 5 is a D₂O reflector behind the D₂-vessel. This is to minimize losses through the insertion port of the cold source due to lack of reflector. This is an important point to consider, since the cold source flux "lives" on thermal neutron influx and cold neutron return through all of its surfaces which are not used for beam extraction.

Unwanted losses can still occur even in a well reflected situation, if the width of the gap between the moderator and the reflector becomes too wide. This effect has been considered by A. Taylor for the case of a cryogenic moderator on a pulsed spallation neutron source, where it is particularly significant. The results are shown in Fig. 6. The space requirement may result from the need of direct moderator chamber cooling, the introduction of safety barriers and other practical requirements. It is important to keep the amount of material low, as well as the "unused" space.

3.3 ADVANCED INSTRUMENT CONCEPTS USING COHERENT PHASE SPACE TRANSFORMATION AT DISCRETE WAVELENGTHS

From Fig. 3 it is obvious that for any desired value of k there is one moderator temperature which yields optimum intensity. This can be easily calculated by differentiating equ. (11) with respect to kT . The result is

$$kT = k/\sqrt{2} = \frac{1}{h} \sqrt{2 m k_B T} \quad (13)$$

which gives the optimum moderator temperature.

Inserting equ. (13) into equ. (11) yields the maximum neutron current density on a neutron guide, that can be obtained by optimizing the moderator temperature as a function of k :

$$j_G^{max.} = \frac{\phi}{\pi} \cdot \frac{4}{k^3} e^{-2} \quad (14)$$

This curve is shown in Fig. 3 as the envelope of the distribution for different moderator temperatures.

For example, for $k = 2.75 \text{ \AA}^{-1}$ ($\lambda = 2.28 \text{ \AA}$) a 100 K cold moderator would yield 3 times more neutrons than either a 35 K or a 350 K moderator.

3.3.1 Coherent phase space transformation to change the magnitude of k

Obviously, it is not practical to devise an optimized neutron moderator for all neutron wave lengths of interest in neutron scattering research. However, an interesting option has been proposed to make use of the high phase space density at low k -values also at higher ones. This is the coherent transformation by means of a high velocity Doppler drive /8/. For example, a Doppler shift by 1000 m/s (e.g. by backwards reflection from

a crystal moving at 500 m/s) corresponds to a k -shift of $1.59 \text{ \AA}^{-1}$. If neutrons from the 35 K-distribution on a neutron guide are shifted by that amount to higher k -values while retaining their original phase space density, the gain as a function of the final k -value is shown in Fig. 7. It increases steeply up to the point, where the 35 K-distribution in Fig. 3 intersects the 350 K-distribution and then starts to drop off again, because from that point on the 350 K-distribution must be taken as the reference value to evaluate the gain. The maximum gain is obtained for $k = 2.75 \text{ \AA}^{-1}$ ($\lambda = 2.28 \text{ \AA}$) where an almost 30-fold increase in intensity would result (ten times more than an optimized cold source!).

Before looking at some practical implications of this technique, it should be mentioned that this gain depends of course on the starting distribution, as can be seen from curve b in Fig. 7 which holds for a 50 K moderator. Note, that the reference is the starting distribution in each case. The curves are only directly comparable where the reference is the 350 K-case (solid part). Otherwise the intensity available without Doppler shift has to be factored in.

Also, on a standard non-reflecting beam hole the situation is less favorable for this technique. This can be seen from equ. (9). The possible gains for this case on a 50 K source are also shown in Fig. 7 (curve c).

An example of an instrument based on a Doppler shift device for high energy transfer on a neutron guide worked out by Alefeld /8/ is shown in Fig. 8.

The rotating Doppler drive with a circumferential speed of 500 m/s is located at a neutron guide. If a crystal is used, which, when at rest, reflects neutrons of 1389 m/s velocity, it will pick neutrons of 889 m/s and transfer them to 1889 m/s, i.e. $3 \text{ \AA}^{-1}$ or $\lambda = 2.1 \text{ \AA}$. According to Fig. 7 this would result in a 22-fold gain in intensity, if a 35 K cold moderators is available, or a 14-fold gain on a 50 K-moderator.

It should be noted that, due to its tilt during the reflecting period, the crystal would automatically pick a time bin of about $32 \mu\text{s}$ from the beam on the neutron guide, thus acting as a chopper at the same time.

The Doppler drive can be designed with several crystals on its circumference, giving the desired pulse repetition rate for the time-of-flight spectrometer. Since this repetition rate is of the order of 100 Hz (50 to 200 perhaps), there is an obvious parameter for optimization:

Compress the cold flux into time intervals in which it can be used. This is of course not possible, if the fast neutron source operates in steady state mode. On pulsed devices, such as pulsed reactors or accelerator driven sources this can be done, however. In this case, the pulse-to-average flux ratio is an important quantity to optimize. In this context the choice of reflector material as well as of the moderator is of importance, because the pulse length and hence also the peak pulse height is significantly affected by the time during which neutrons are fed into the cold source by the reflector.

Experiments carried out at SIN and KENS on liquid H₂-moderators have confirmed this. Results for the measured pulse decay times are shown in Figs. 9a and 9b. It should be noted that in the SIN-experiments (Fig. 9a) the reflector material directly surrounded the H₂-moderator, thus representing the true effect of the different reflectors. In the KENS-experiment the H₂-moderator was surrounded by a 3 cm polyethylene layer, followed by a graphite reflector. It must be assumed, that this polyethylene effectively decouples the hydrogen moderator from the graphite reflector and the time constant $\tau = 200 \mu\text{s}$ is strongly affected by the polyethylene. Nevertheless, such an arrangement is very favourable in terms of heat load on the cold moderator, and possibly also in terms of cold moderator efficiency. This can be seen by the intensities measured at KENS for different environments at a H₂ moderator as shown in Fig. 10. (Note: The paper gives no indication whether there was a larger gap between moderator and reflector in the case of 0 premoderator thickness or not. If so, some of the gain from adding a premoderator might simply result from reducing the gap; see findings by A. Taylor, quoted in Fig. 6).

The reflector used of course also affects the peak and average neutron flux. Results for the SIN-experiments are tabulated in Table 1. These results hold for a proton pulse duration of $250 \mu\text{s}$. Nevertheless, it is obvious that the gain which is possible in the peak flux by going to a fast, non-moderating reflector is compromised by a loss in time average flux and vice versa.

If an effective moderator temperature around 35 K can be achieved, as is the claim from the KENS-measurements [...], the combined advantage from a pulse structure and a $1.59 \text{ } ^\circ\text{A}^{-1}$ Doppler shift can be as high as 500 or more relative to an instrument picking this energy directly from a steady state Maxwellian spectrum, at the same time average flux.

3.3.2 Coherent phase space transformation changing the shape of the phase space volume

Exploiting the pulse-to-average ratio of cold neutrons on an intensity modulated source is not limited to the transformation back to "warm" neutrons. For another important instrument, the back scattering spectrometer, there exists a significant potential for intensity improvement which, again, can be enhanced by having a time structure available (Schelten and Alefeld) /11/.

Again, phase space transformation is used, but this time by a mosaic crystal moving parallel to its lattice planes during the reflection. The aim is to solve a problem common to all back scattering spectrometers located on neutron guides: the mismatch in angular divergency between the incident and the analyzed phase space volume: On a neutron guide the angular divergency is of the order of 0.01 rad, whereas the analyzer crystals can accept of the order of 0.2 to 0.4 rad without seriously affecting the necessary Q-resolution.

Fig. 11 shows the momentum diagrams for Bragg reflection from a mosaic crystal at rest (Fig. 11a) and when moving at a velocity v_k parallel to its lattice planes (Fig. 11b). In general Bragg reflection from a mosaic crystal broadens the angular distribution without affecting the overall momentum spread Δk_z of the reflected volume (Fig. 11a). Trans-

forming the incident volume into the frame of reference of the moving crystal by simple vector addition and transforming it back to the laboratory frame of reference after the Bragg construction may result in a situation where, in the laboratory frame of reference, the reflected volume is perpendicular to the mean neutron momentum vector.

As can be seen from Fig. 11b, a larger volume element is picked to start with, and the radial momentum spread $\Delta k_{z,1}$ is narrower than in the case where the crystal is at rest. It is, however, still much larger than in the case of a neutron back reflection. This is the reason, why this phase space volume can be scanned by the Doppler drive of a back scattering spectrometer.

Schelten and Alefeld gave a number of parameter sets which can be used to work out a detailed design of such an instrument. The gain in intensity incident on the sample was determined to be of the order of 15, if the source is not pulsed.

A schematic diagram of such an instrument is shown in Fig. 12a. The neutrons exiting from the neutron guide first hit the moving crystal which transforms the phase space volume in shape as described before. They are deflected to the scanning Doppler monochromator as in conventional back scattering instruments, with the exception that now a much wider angular range is covered. The highly monochromatic neutrons from this monochromator hit the sample with their energy varying in time according to the instantaneous velocity of the Doppler drive at the moment of reflection. The analyzer part is conventional.

It is of particular advantage to use this instrument on a source with time structure for three reasons:

1. Construction of the horizontally moving crystal is much facilitated if the condition must only be fulfilled periodically for short time intervals.
2. During these intervals the full pulse intensity can be used whereas conventional back scattering spectrometers always have less than 50 % duty cycle.
3. Most importantly: the moving Doppler monochromator can be replaced by a set of stationary monochromators with grating lattice parameters which, rather than causing a time-dependent energy change reflect all desired energies over the full pulse interval but with an appropriate delay to separate the different energies due to their spatial separation (Fig. 12b). If the lattice parameters of the crystals are adjusted such that the reflected wavelengths are just one back reflection width from each other, the whole band of energies covered by the moving Doppler crystal can also be covered by this stack of crystals. For a pulse width of the order of 200 μ s, time separation of the different energies can be easily achieved by a flight path difference resulting from a spatial separation of the layers in the stack. ($t v = 600$ m/s, 200 μ s require 2×100 μ s flight path or a crystal separation of 6 cm.) In this way another substantial gain of one order of magnitude or more is possible by this "multiplexing" technique, bringing the total intensity gain over a conventional back scattering spectrometer on a steady state cold source up to a factor of a few hundred, depending on details of the design.

The two examples quoted above show convincingly, that by exploiting an extra degree of freedom, namely the details of the time structure in a high flux intensity modulated neutron source, gains in useful neutrons can be achieved also in the cold neutron regime, which can not nearly be reached by any other optimization concern, especially since they are on top of anything that can be gained by other means.

4 CONCLUSIONS

Obviously, the scope for cold neutron source optimization becomes extremely broad, if non-standard uses of the cold neutrons are considered, especially if a time structure of the source is to be exploited for effective neutron fluxes which are inaccessible in steady state neutron source operation.

The option of taking advantage of an intensity modulation is particularly important in cold moderators, because here, even more than in the primary neutron producing zone, the possibility of heat removal tends to limit the total time average flux that can be produced.

The examples quoted, although particularly spectacular, are by no ways the only ones of this kind. Many ways have been proposed to make more efficient use of the neutrons once moderated. This principle becomes the more important, the more difficult it becomes to make available more moderated neutrons, be it because of limitations in the primary neutron production or in the moderating devices themselves. Most of the new developments to improve instrument efficiency /12/ work on neutrons in the sub-thermal and cold energy regime. In this context, also methods of using electromagnetic forces on the neutron spin to effect certain phase space transformations, as proposed by Rauch and coworkers on various occasions /13/ may become of particular interest.

With neutron economy being the prime optimization concern; intensity modulation and phase space transformation provide an economic way of neutron usage!

REFERENCES

- /1/ R.A. Little and R.G. Alsmiller
"Design Calculations for the ANS cold source" in "Advanced Neutron Sources 1988"
Institute of Physics Conference Series No. 97, D.K. Hyer, ed. Bristol and New York, 1989, pp. 205 - 216
- /2/ A. Michaudon
"Reactor Science and Technology" (J. Nucl. En. A/B) 17, pp. 165 - 186 (1963)
- /3/ R.N. Silver and M.W. Johnson
"Workshop summary on data treatment and techniques" in "Advanced Neutron Sources 1988"
Institute of Physics Conference Series No. 97, D.K. Hyer, ed. Bristol and New York, 1989, pp. 735 - 737
- /4/ R.N. Silver, D.S. Sivia and R. Pynn
"Information content of line shapes" in "Advanced Neutron Sources 1988"
Institute of Physics Conference Series No. 97, D.K. Hyer, ed. Bristol and New York, 1989, pp. 673 - 683
See also remarks by R. Pynn, this conference.
- /5/ F. Atchison, W. Bucher, A. Höchli, I. Horvath and L. Nordström
"The D₂ cold-neutron source for SINQ" in "Advanced Neutron Sources 1988"
Institute of Physics Conference Series No. 97, D.K. Hyer, ed. Bristol and New York, 1989, pp. 473 - 482
- /6/ F. Atchison, G. Bauer, W. Fischer, K. Skala and H. Spitzer
"The cold neutron moderator for the continuous spallation neutron source SINQ" this conference
- /7/ A.D. Taylor
"Neutron Transport from Targets to Moderators" in Proc. Meeting on Targets for Neutron Beam Spallation Sources
Jülich, 1979 Report Jül-Conf-35
G.S. Bauer and D. Filges, eds.

- /8/ B. Alefeld and N. Nücher
in "Realisierungsstudie zur Spallations-Neutronenquelle"
Jül-Spez-113 and KfK 3175 (1981), pp. 125 - 135
- /9/ G. Bauer, H. Conrad, W. Fischer, K. Grünhagen and H. Spitzer
Proc. ICANS-VIII Report RAL-85-110, pp. 344 - 354
- /10/ N. Watanabe, Y. Kiyanagi, K. Inone, M. Furusaka, S. Ikeda, M. Arai and H. Iwasa
"Preliminary optimization experiments of coupled liquied hydrogen moderator for KENS II" in "Advanced Neutron Sources 1988"
Institute of Physics Conference Series No. 97, D.K. Hyer, ed. Bristol and New York, 1989, pp. 787 - 797
- /11/ J. Schelten and B. Alefeld
"Back Scattering Spectrometer with Adapted Q-Resolution at the Pulsed Neutron Source"
in "Proc. of the Workshop on Neutron Scattering Instrumentation for SNQ, Maria Laach, 1984, Report Jül-1954, H. Stiller and R. Scherm eds., pp. 378 - 389
- /12/ G. Bauer and R. Scherm
"Forthcoming Instrument Developments for Improved Utilization of Neutron Beams"
in "Neutron Scattering", G.H. Lander and R.A. Robinson, eds. North Holland, Amsterdam, 1986
- /13/ L. Niel, G. Badurek, H. Rauch, J. Summhammer, H. Weinfurter
"Neutron beam handling by inelastic interaction with time-dependent magnetic fields "
in "Advanced Neutron Sources 1988"
Institute of Physics Conference Series No. 97, D.K. Hyer, ed. Bristol and New York, 1989, pp. 829 - 836

Reflector material and dimensions [cm ³]	Pulse decay time τ [10 ⁻⁶ s]	$\hat{\Phi}/\bar{\Phi}$	Neutron pulse width (for a proton pulse width of 250 μ s)	Relative peak intensity	Relative average cold flux
D ₂ O 170 x 170 x 85	710	12	620	0.72	1.2
C (cooled) 120 x 120 x 80	350	20	390	1	1
Pb 60 x 60 x 60	230	27	320	1.1	0.8

Table 1 Data derived from spectral measurements on an H₂-cold source mock up at SIN with different reflector materials

Fig. 1 Reduced phase space density distributions for moderators of different temperatures T_{mod} as a function of neutron wave number k .

Fig. 2 Spatial neutron flux distribution inside a volume of liquid deuterium embedded in a D_2O reflector and viewed by an extraction void for the cases without and with reentrant cavities of different depths. (from ref. /1/).

Fig. 3 Relative intensity of neutrons on a neutron guide for different moderator temperatures as a function of neutron wave number k . The maximum intensity possible for any value of k by optimizing the moderator temperature is given by the curve $I_{\text{max}}^{\text{NG}}$, which is proportional to k^{-3} .

Fig. 4 Neutron transmission through layers of D_2O of different thicknesses as a function of neutron wave length. (from ref. /5/, see text).

Fig. 5

Horizontal section through the part of the SINQ-cold moderator close to the target. A T-shaped system of channels in the D₂O tank avoids the need for cold neutrons to cross a warm D₂O-layer upon extraction. The cryogenic gap has been minimized and a D₂O-auxilliary reflector has been introduced to avoid cold neutron losses. (see also ref. /6/).

Fig. 6

Cryogenic penalty incurred as a function of the width of the gap needed for structural materials on a cold moderator. (from ref. /7/).

Fig. 7 Possible gain factors resulting from a coherent phase space transformation by 1.59 Å^{-1} on a neutron guide for cold moderators of different temperatures as a function of the final wave numbers. The reference for the solid part of the curves is a 350 K Moderator of the same flux.

Fig. 8 Design principle of a thermal TOF-spectrometer using coherent phase space transformation on a neutron guide viewing a cold moderator (from ref. /8/).

Fig. 9 Semi logarithmic plots of neutron pulses from liquid-H₂ moderators with reflectors.

(a) Measurements at SIN /9/ for Pb, C and D₂O as reflector materials; fast neutron pulse duration 250 μs

(b) Measurement at the Hokkaido electron linac /10/ for very short fast neutron pulses and a graphite reflector with 3 cm polyethylene premoderator around the H₂-moderator.

Decay times have been deduced from the slopes of the straight lines used to approximate the measured data.

Fig. 10

Comparison of intensities as a function of neutron energy measured at the Hokkaido-linac for different environments of an H_2 moderator. "Bare hydrogen" means without graphite reflector. The solid curves represent Maxwell distributions fitted to the measured data and used to determine the effective moderator temperature which was found to be around 35 K in all cases.

Fig. 11

Momentum space representation of a Bragg reflection from a crystal of reciprocal lattice vector τ .

(a)

crystal at rest; $\Delta k_{z,0} = \Delta k_{z,1}$

(b)

crystal moving parallel to its lattice planes at velocity v_k ; $\Delta k_{z,1} < \Delta k_{z,0}$.

Fig. 12 Sketch of the design principle for a back scattering spectrometer using a horizontally moving crystal (phase space crystal).

(a) With classical revolving Doppler monochromator

(b) With a set of spatially separated monochromator crystals with appropriately grated lattice parameters to separate pulses of reflected neutrons in time.

Some Remarks on Design Criteria and Optimization Concerns for Cold Neutron Sources

Gunter Bauer

Questions/Answers/Comments

(G. Russell/T. Scott)

Question: You mentioned "stable" moderation temperature as an important moderator design consideration. What do you consider acceptable?

Answer: Probably five degrees in temperature fluctuation can be tolerated as a general rule. Of course, this depends on what range of energies is used and how much of the Maxwellian part of the spectrum is included. In the slowing down regime, the influence of the effective moderator temperature is relatively small. In the Maxwellian regime, where poisoning is used to shorten the pulses, the phase space density, and hence the extracted intensity, depends more seriously on the moderator temperature as can be seen from the formulas I used.

(J. Carpenter)

Comment: Experience with Intense Pulsed Neutron Source Liquid CH₄ moderators is that experimenters accepted a 5 K temperature band, but complained if the band was 10 K. Of course, proper use of beam monitors reduces the sensitivity to variation of moderator temperatures. As experiments and users become more sophisticated, their demands will tend to become more strict.

(R. Pynn)

Question: Most of your remarks and optimization criteria have been specifically tailored for short-pulse spallation sources or reactor sources. Are there any additional criteria that are implied by the different ways in which we can imagine using an intensity-modulated source?

Answer: Intensity-modulated sources imply a high time-average flux. In this sense, the criteria for reactors apply. There is not much concern about pulse shape. This makes optimization easier in some respects than on pulsed sources. The real concern is the efficient compression of a high-flux into pulses of high-intensity, which may mainly affect the choice of reflector material. Like in pulsed sources, tailoring of individual moderators and their reflectors to the requirements posed by the spectrometers is possible. Intensity-modulated sources open up a wider field of cold neutron uses than pulsed sources or steady-state sources alone, and therefore, will also broaden the range of optimization concerns.

Some Remarks on Design Criteria and Optimization Concerns for Cold Neutron Sources

Gunter Bauer

Questions/Answers/Comments

(P. Ageron)

Question:

Is the T-shaped tube of the Cold Neutron Source project in the SINQ changeable independent of the D₂O tank, or is it welded to the tank?

Answer:

For the present design of the SINQ moderator tank, we do not provide for the possibility of exchanging beam tubes. In terms of thermal neutron flux, SINQ will be roughly comparable to a DIDO-type reactor, where the beam-tube noses also cannot be exchanged. Because at SINQ we may have a slightly higher damage rate from high-energy neutrons, we have considered the option of exchanging the whole moderator tank, which would of course be a major operation and hopefully never become necessary.

Heating Rates in Reactor and Spallation Cold Sources

Walter E. Fischer

Paul Scherrer Institute
CH - 5232 Villigen PSI, Switzerland

ABSTRACT

We discuss the different nature of the heating by the nuclear radiation field in the vicinity of a spallation target and a reactor core. An attempt to compare the heating rate is made.

I. INTRODUCTION

The aim of this presentation is to find a fair comparison of the heat load in cold sources between beam tube reactors and spallation neutron sources. While the figure of merit for a reactor source (average neutron flux) is straightforward, the corresponding definition is more involved for pulsed spallation neutron sources. We shall consider this point at the end of the paper.

An unambiguous comparison is, however, possible between a reactor and the continuous spallation source SINQ, which is under construction at PSI [1]. Since both devices - with the exception of the neutron generating part - are built up in a rather similar way, the heat load for equal thermal flux is a fair figure of merit. For these cases, the relative merit of the fission- and spallation-reaction as a basic neutron generating mechanism can be appreciated.

Let us, therefore, firstly compare these two neutron generating reactions:

Figure 1
Spallation neutron spectrum for an incident 590 MeV proton beam on a thick cylindrical lead target with diameter of 10 cm. Spectrum measured under 90° with respect to target axis.

THE SPALLATION REACTION

- Neutron Spectrum

This spectrum consists of two parts reflecting the two stage process of spallation. Figure 1 shows this neutron spectrum from the bombardment of a thick cylindrical lead target by 590 MeV protons [2]. This spectrum has been measured under an angle of 90° with respect to the target axis. The shoulder for the energy region $E > 20$ MeV due to direct knock out reactions is clearly visible. The low energy part of the spectrum – essentially a Maxwellian – is due to the neutron evaporation process. Clearly, these are the neutrons which are of interest in a spallation source.

Their angular distribution is isotropic, whereas the distribution of the high energy component is peaked into the forward direction. These properties are demonstrated in the polar graph (Fig. 2).

- Gamma Spectrum

We do not intend to discuss the gamma spectrum of the spallation process here. We just want to emphasize that for one incident proton, only one heavy isotope emitting prompt gamma rays is produced. This spallation reaction delivers eight useful evaporation neutrons. Furthermore, at these proton energies π^0 -production is possible. The π^0 decays into two energetic gammas. However, the production process is comparatively rare.

Angular Distribution of Leakage Neutrons from the SINQ PbBi Target

Figure 2

Polar plot, showing the angular distribution of high energy spallation neutrons.

Monte Carlo run:

Proton energy: 590 MeV.

Target: Pb-Bi cylinder with 18 cm diameter and 100 cm length.

THE FISSION REACTION

- Neutron Spectrum

The neutron spectrum of the nuclear fission process is very similar to the evaporation part of the spallation spectrum. No high energy neutrons are emitted in fission processes.

- Gamma Spectrum

In the chain reaction of a reactor core two isotopes emitting prompt gamma rays are

produced for approximately one useful neutron.

Qualitatively we may conclude that the spallation process dissipates a considerable fraction of the energy involved by high energy neutrons. As a gamma source, however, a spallation source is of relatively modest strength. For a fission core as neutron source we expect the situation to be vice-versa. For the nuclear heating in the vicinity of a neutron generating source the following scheme seems to be valid:

DOMINANT RADIATION FIELD FOR HEATING

REACTOR CORE	-	GAMMA RADIATION
SPALLATION TARGET	-	HIGH ENERGY NEUTRONS

Obviously the heating efficiency of either field depends also on the heated material.

The heating due to neutron-capture gammas is for both devices proportional to the epi- and thermal neutron flux and is also dependent on the structure material used.

Beam tube reactors are in operation since the early sixties. By now, nuclear heating in reactors is quite well known. With spallation sources the situation is different. Being in operation since a few years only, their potential of optimization has most likely not yet been exploited. A few years ago we therefore decided to define and find some sort of benchmark for investigation of nuclear heating in spallation sources. This benchmark was supposed to have the following properties:

- i) It should give a valuable reference for nuclear heating in spallation sources.
- ii) It should provide a possibility of comparison with reactor sources.
- iii) It should already exist and allow a quick access to proceed the experiment.

Of all the existing particle beam driven neutron sources the TRIUMF facility in Vancouver [3], which is mainly used as an isotope production station, came nearest to these requirements.

II. MEASUREMENT OF NUCLEAR HEATING IN THE VICINITY OF A SPALLATION TARGET

The TRIUMF facility (Fig. 3) consists of a lead target which is surrounded by a reflector. The lower part of the reflector is D_2O , the upper H_2O . A rectangular aluminium shaft gives access to a position in the D_2O -reflector, approximately 10 cm from the surface of the target cylinder. Various test samples of different materials were positioned in thermal isolation at this location in order to measure their heat load calorimetrically [4].

With a beam energy of 500 MeV and a current of $10\ \mu\text{A}$ (5 kW beam power) the environment of the shaft could be kept on constant temperature. Hence, the heat loss of the sample – which was by far dominated by thermal radiation – was only a function of its own temperature. The principle of the measuring procedure has been described in Ref. 4.

Figure 3 Schematic view of the TRIUMF neutron facility.

The energy sources contributing to the temperature rise of the samples are:

- high energy and fast neutrons
- charged particles possibly escaping the target
- gamma radiation incl. π^0 -decay
- capture gammas due to epi- and thermal neutron capture in the shaft and the sample

The last contribution could be estimated, using the thermal neutron flux which was continuously measured at the sample position. This heat source was particularly large for the Cu and W sample. In order to show the systematic behaviour and the dependence on the atomic number of the direct heating by the neutron and gamma field, we subtract the (n,γ) part from the total heat load measured. The data are shown in Fig. 4.

Figure 4
Heat deposition per gram in various samples by fast and high energy neutrons and gamma rays. The (n,γ) contribution is subtracted. (For dashed and dot-dash line see text.)

The values for H₂ and D₂ have been extracted from measurements in H₂O and D₂O using the stoichiometric ratio to oxygen which we assumed to have a heat load between carbon and aluminium. All solid samples were chemically pure as available.

The slopes of the straight lines in Fig. 4 represent the A-dependence of the energy transfer by the high energy neutron spectrum due to elastic and inelastic neutron scattering as obtained by a Monte Carlo run. If we believe these slopes to be correct, we may extract the ratios of the various possible heating mechanisms. Here are the results:

HEATING CONTRIBUTIONS:

HEAVY ELEMENTS

W, Pb, Bi

$$\dot{Q}_\gamma/\dot{Q}_n = 5/1$$

INTERMEDIATES

Fe, Cu

$$\dot{Q}_\gamma/\dot{Q}_n = 1/1$$

LIGHT ELEMENTS

NEUTRON HEATING DOMINATES
BY A FACTOR 3 TO 4

Let us now look at the data of hydrogen and deuterium. According to these values the power transfer per atom is

$$\begin{array}{ll} 6 \cdot 10^{-23} \text{ mW/at} & \text{for hydrogen and} \\ 6.4 \cdot 10^{-23} \text{ mW/at} & \text{for deuterium} \end{array}$$

Due to the higher moderation efficiency for fast neutrons in hydrogen one would expect a much higher value for hydrogen than for deuterium. Since this is here not the case, we conclude that the evaporation neutrons are already thermalized to a large extent by the 10 cm layer of D₂O between the target and the sample. Corresponding Monte Carlo calculations indeed verify this.¹ We therefore conclude that the heating of hydrogen and deuterium is predominantly due to the high energy neutrons.

This has consequences when using the data for heat load estimates at pulsed spallation neutron sources. Normally, for reasons of pulse shape optimization, these sources have no premoderating layer between target and e.g. cold moderator. In this case the heating of a liquid hydrogen source is considerably stronger, due to the contribution of the slowing down of the evaporation neutrons. We shall come back to this point.

III. HEATING OF COLD SOURCES

We are now ready to put the heat load data of various neutron sources into perspective. We compare first two continuous sources, namely

- the high flux reactor at ILL
- the medium flux spallation source at PSI

Both devices have (or plan to have) a liquid D₂ cold source embedded in a D₂O reflector. From the point of view of environment and material composition they are rather similar.

ILL: D₂ source 25 ℓ

Distance from source center to the core axis is 70 cm

Thermal flux at coupling radius $4 \cdot 10^{14} \text{ n/cm}^2\text{s}$

Nuclear heating power: 6.5 kW [5]

¹There would of course have been the possibility to repeat the whole measuring program with a drained D₂O tank. Originally, we intended to proceed that way. Unfortunately other obligations and the corresponding lack of time prevented us from doing so.

SINQ: D₂ source 21 ℓ

Distance from source center to the core axis is 37 cm

Thermal flux at coupling radius $1 \cdot 10^{14}$ n/cm²s

Nuclear heating power: 2.2 kW [6]

The heat flux in the region of the highest thermal load is 0.6 W/cm² for the old source of ILL and will be 0.2 W/cm² for the SINQ source. It would seem that these figures favor somewhat the fission process. However, since the SINQ target considered here is not yet optimized concerning the neutron economy we conclude:

THE HEATING OF A LIQUID D₂ SOURCE FOR THE TWO NEUTRON GENERATING MECHANISMS IS ROUGHLY EQUIVALENT

and this in spite of the different dominant heating modes, namely

GAMMA FIELD FOR THE REACTOR HIGH ENERGY NEUTRONS FOR THE SPALLATION SOURCE

For a liquid H₂ source we can make the following comparison[6][7]:

DIDO (KFA Jülich)

H₂ source in a D₂O reflector at a thermal flux of $0.8 \cdot 10^{14}$ n/cm²s

Heat density: 1.2 W/g in the aluminium can
4.2 W/g in the liquid H₂

SINQ

At an equivalent position in the D₂O reflector

Heat density: 1.5 W/g in the aluminium can
3.2 W/g in the liquid H₂

This confirms the statement above.

Let us now discuss the heating rate of cold sources in pulsed spallation sources. I could find the following references: [8], [9].

- **KENS** (Tsukuba)

Proton energy 500 MeV

Solid CH₄ - cold moderator with a volume of 900 cm³

The total heat load is 1 W/μA

- **ZING-P'** (a precursor of IPNS at Argonne)

Proton energy 300 MeV

Liquid H₂ - moderator with a volume of 370 cm³

The total heat load was 0.2 W/μA

We can scale these two cases to the same proton beam power and moderator volume and obtain as a typical reference value for the heat load in a pulsed spallation source

$$1 \text{ mW/cm}^3 \mu\text{A}$$

A comparison with the H_2 source of SINQ shows that this reference value is 56% higher. Most likely this discrepancy is partially due to the slowing down of neutrons, which in the case of SINQ takes place in the D_2O reflector. Furthermore, both facilities use a depleted uranium target. Additional gamma heating, particularly in heavier materials such as decouplers or structure material may be considerable.

IV. NEUTRON ECONOMY

The nuclear heating of cold sources for fission and spallation reaction driven neutron generators is roughly equivalent. For genuine pulsed spallation sources which are optimized to short pulses for TOF-techniques the heat load is even 50% higher. The real advantage of pulsed spallation sources is due to the more economic use of the neutrons produced. In the extreme case the peak flux becomes equivalent to the average flux of a continuous source.

However, particularly for experiments with cold and very cold neutrons, e.g. inelastic scattering at high resolution, this striking advantage diminishes. Nevertheless, it has been shown that there exist other possibilities to exploit the time structure of a neutron burst other than strict time of flight technique. Various methods have been discussed[10]:

- Correlation time of flight
- Phase space transformation (moving crystals)
- Multiplexing techniques

For these techniques the very short neutron pulses are not essential. The tough compromise between flux and pulse length can be relaxed (up to 0.5 ms, say), and a higher average flux can be achieved.

Let τ be the pulse length from a moderator. The effective peak flux is then

$$\langle \Phi \rangle_\tau = \frac{1}{\tau} \int_{t_0}^{t_0+\tau} \Phi(t) dt$$

which for $\tau \rightarrow 0$ approaches the peak flux $\hat{\Phi}$. Now, τ cannot be made arbitrarily small for an efficient cold source. Indeed $\tau(\lambda)$ is a monotonically increasing function of the wave length.

Let T be the time interval between to pulses and Δt the time needed to collect the useful data of the events from one pulse. The gain at the actual instrument can be defined as

$$G = \frac{\langle \Phi \rangle_\tau}{\hat{\Phi}} \cdot \frac{\Delta t}{T}$$

Obviously, the aim is permanent "business" in the data taking procedure, that is: $\frac{\Delta t}{T} \rightarrow 1$.

$\frac{\langle \Phi \rangle_r}{\bar{\Phi}}$ is then a measure for the "neutron economy":

$\langle \Phi \rangle_r$ determines the figure of merit

$\bar{Q}$ represents a measure for the heat load.

As a reference we mention the predicted performance of the SNQ project.

$\hat{\Phi}/\bar{\Phi} = 35$ at an average flux of $\bar{\Phi} \sim 10^{15}$ n/cm²s. The heat load on the cold source is hence roughly the same as in a high flux reactor, and we know that this is feasible. Depending on the instruments the economy factor is

	THERMAL REGION	COLD REGION
$\frac{\langle \Phi \rangle_r}{\bar{\Phi}}$	10 - 35	5 - 20

References

- [1] W.E. Fischer, Nucl.Instr.and Methods, **A249**, 116 - 122 (1986).
- [2] S. Cierjacks, F. Raupp, S.D. Howe, Y. Hino, M.T. Swinhoe, M.T. Rainbow, L. Buth, ICANS-V, June 22 - 26, 1961, Jülich-Conf., 45 (1981).
- [3] A.S. Arrot, T.L. Templeton, I.M. Thorson, R.E. Blaby, J.J. Burgerjon, T.A. Hodges, R.R. Langstaff, TRIUMF Report, 77-1 (1977).
- [4] W.E. Fischer, L. Moritz, H. Spitzer, I.M. Thorson, Nucl.Science and Engineering, **93**, 273 (1986).
- [5] P. Ageron, this conference.
- [6] W.E. Fischer, PSI, SINQ 816 FIN-712 (1987).
- [7] C. Doose, Kerntechnik, **12** 528 (1971).
- [8] S. Ikeda, Y. Ishikawa, K. Inoue, ICANS-IV, Oct. 20 - 24, 1980, KEK, Tsukuba.
- [9] J.M. Carpenter, M. Kimura, R. Kleb, M. Misawa, R.H. Stefiuk, D.F.R. Mildner, Nucl.Instr.and Methods, **198**, 447 (1982).
K. Kimura, J.M. Carpenter, D.F.R. Mildner, Nucl.Instr.and Methods, **198**, 433 (1982).
- [10] R. Scherm, H.H. Stiller (Eds.), Proc. Workshop on Neutron Scattering Instrumentation for SNQ, Maria Laach, 3 - 5 Sept. 1984, Jülich-Rep. 1954 (1984).

Heating Rates in Reactor & Spallation Cold Sources

Walter E. Fischer

Questions/Answers/Comments

(D. Woods)

Question:

What thickness of premoderators at LANSCE would you advise in order to take off the heat loads from the cold moderators?

Answer:

A few centimeters of hydrogen-containing material would do it. However, I am not sure whether the deterioration of the pulses would be tolerated.

(G. Russell)

Comment:

In reference to Dick Woods question on premoderating the LANSCE cold source, for the lightly decoupled LANSCE liquid H₂ source, the pulse broadening of neutrons may not be too significant.

(N. Watanabe)

Question:

How important is the contribution of β -decay heating in your system? I think it will be much smaller than the neutron heating.

Answer:

I do not recall the numbers right now; however, compared to the heating due to high-energy neutrons in light materials, the contribution of β -decays is negligible.

(N. Watanabe)

Comment:

The proton beam energy at KENS is not 800 MeV but 500 MeV.

An Alternative in the Heat Transfer Design: A Cold Neutron Source Without Vacuum Insulation

Paul Ageron

Institut Laue - Langevin, 156X 38042 Grenoble Cedex, France

ABSTRACT

The suppression of the vacuum insulation in a cold neutron source may allow the use of thin magnesium materials at low temperature, thus a considerable reduction of the nuclear heating in a high or superhigh flux reactor.

1. INTRODUCTION

All existing cold neutron sources are designed as simple cryostats where a tight vessel containing the cold moderator fluid (at 20 to 50 K) is surrounded by a vacuum, itself contained in one or several pressure vessels maintained at room temperature.

The heat generated in the fluid and in the vessel by heat losses and mainly by nuclear heating is evacuated:

- (i) by forced circulation of helium gas at low temperature in tube or heat exchange in thermal contact with the cryogenic cell which cools also the cold moderator (a typical example is the cold source of HFBR at BNL);
- (ii) by natural convection of the moderator liquid (ILL or Orphee cold sources) or by forced circulation of the supercritical hydrogen (cold sources of the "RISO" type).

Technical advantages and problems of these two designs have been described in existing or future sources including combination of the two designs.

In high or ultra high flux reactors, where the problems of nuclear heat generation and of stresses in irradiated materials at low temperature become much more important than the heat losses, one can consider to remove the vacuum jacket if this contribute to solve the problems.

2. DESIGN OF A SOURCE WITHOUT VACUUM INSULATION

A vacuum insulation necessitates that the cold moderator container will fulfill the following conditions:

- to withstand a pressure of 1-4 bar for liquid hydrogen or deuterium or 15 bars for supercritical hydrogen;
- to have a very good tightness to hydrogen;
- to have a proven good behaviour under irradiation at low temperature.

Operating experience of existing cold neutron sources shows that aluminium (either pure or with a few percent of magnesium) in thickness of more than 1.5-2 mm is a convenient material and presently the main one used.

The counterpart is its high nuclear heating due to thermal cold neutron absorption, the beta emission and the silicon build up in the ^{28}Al decay. For a ultra high flux reactor this too high heat load would make the heat evacuation by natural circulation of the boiling moderator very difficult or impossible. If the vacuum space is replaced by a stagnant gas of the source nature and at the same pressure as the moderator, all the above requirements are no longer necessary. The "aluminium container" (2 mm thick, i.e. 0.5 g cm^{-2}) may be replaced for instance, by a thin "magnesium separator" (0.6 mm thick, 0.1 g cm^{-2} or less).

There is now an experience of 5 years of operation of such a separator which delimit an open gas cavity in communication with the liquid moderator of the ILL vertical cold source.

The reduction of the nuclear heating to be evacuated at low temperature would be enormous: the extrapolation of the ILL vertical cold source to a reactor with a power and a flux 5 times higher gives:

TABLE I

Design		Conventional		Without evacuated insulation	
		D2	Al	D2	Mg
Mass of cold materials	kg	3.6	2.5	3.6	0.5
Specific nuclear heating	kw/kg $n+\gamma$	2.6	3	2	2
	β	0	3	0	0
Total power	kw	9.4	15	7.2	1

3. OPTIMIZATION OF A "STAGNANT" GAS INSULATION

The heat losses between the outer hot container and the cold moderator are negligible with an evacuated gap (0.01 watt/cm^2 by radiation with a 0.1 coefficient of emissivity); they are more important and should be a compromise between the establishment of natural convection and nuclear heating of the material which should prevent it (fibers, screen).

The difference of the integrals of conductivity $\Lambda(T)$ through a gap of stagnant gas of thickness a and a conductivity $\lambda(T)$, which transmits a heat flux ϕ and has an internal heat generator per unit of volume q is given by :

$$\Lambda(T(o)) - \Lambda(T(a)) = \frac{qa^2}{2} + \phi a$$

for gaseous deuterium, the heat conductivity is proportional to temperature

$$\lambda(T) = K T \quad (K \text{ about } 4 - 5 \cdot 10^{-6} \text{ w cm}^{-1} \text{ K}^{-2})$$

$$\Lambda(T(o)) - \Lambda(T(a)) = (T(o) - T(a)) \cdot K (T(o) + T(a)) / 2$$

Thus, it is a sufficient approximation to consider the gas with a constant heat conductivity at the mean temperature $(T(o) + T(a)) / 2$.

The coupling of this gas with the containment wall (thickness a' , mean conductivity λ' , internal heating q') is now described in a simple way, and the temperatures are given by:

$$\text{in wall : } T(x) = T'(o) - \frac{q'x^2}{2\lambda'} - \phi'(o) \frac{x}{\lambda}$$

$$\text{in gas : } T(x) = T(o) - \frac{qx^2}{2\lambda} - \phi(o) \frac{x}{\lambda}$$

with the conditions at the interface :

- equality of temperature $T(o) = T'(o)$
- equality of heat fluxes $\phi(o) = \phi'(o)$

and at the outer boundaries :

- of the wall $T'(-a')$ imposed by the water cooling
- of the gas gap $T(a)$ imposed by the liquid deuterium

This approximation gives in particular a simple expression for the heat flux through the stagnant gas insulation :

$$\varphi(a) = q_a \left(1 - \frac{r/2}{r+r'}\right) + q'a' \frac{r'/2}{r+r'} + \frac{T(-a') - T(a)}{r+r'} \quad \text{where } r = \frac{a}{\lambda} \text{ and } r \leq \frac{a'}{\lambda}$$

are the thermal resistances, per unit of surface, respectively of the gas gap and of the wall. If one takes (specific heating 2 W g^{-1}) :

TABLE II

	boundary	T K	a cm	λ $\text{w cm}^{-1} \text{K}^{-1}$	ρ g cm^{-3}	q_a w cm^{-2}
Zircalloy wall		330	.5	.16	6.5	6.5
D2 gas gap		30	2	$7 \cdot 10^{-4}$	(variables)	

The heat flux $\varphi(a) = \frac{1}{2} q_a + 0.1033$ is linear with the nuclear heating of the insulating material; for instance $q_a = 0.136$ for 4 .Mg screens 0.1 mm thick
 $= 0.4$ for 2 cm of graphite wool with a density of 0.1

It would be minimum for non insulating materials $q_a = 0$: $\varphi(a) = 0.1 \text{ watt cm}^{-2}$, due mainly to the temperature difference $T(a) - T(-a')$, but a natural convection would be possible and would multiply the stagnant gas heat conductance λ/a by a factor :

$$E = 0.1 \text{ (Raleigh number)}^{0.3}$$

The Raleigh (Grashof x Prandlt) divided by $a^3 \times \Delta T$ is given in Fig. 1 for deuterium and nitrogen. For $a = 2 \text{ cm}$ and $\Delta T = 300 \text{ K}$.

the Raleigh for D2 at 200 K is $1.7 \cdot 10^5$

thus $E = 3.8$ and the heat flux $\varphi = E \frac{\lambda}{a} \Delta T = 0.4 \text{ W cm}^{-2}$

4. EXPERIMENTAL VERIFICATION

An annular space 25 cm high, with an inner cylinder ID = 6 cm maintained at liquid nitrogen temperature (80°K) and an outer cylinder OD = 10 cm) maintained at room temperature (300 K) was filled with various insulations in gaseous nitrogen. The flow rate of evaporated nitrogen of the bath in the inner container is a measurement, after stabilisation of the lateral heat loss.

Fig. 1 Raleigh Number divided by
Channel width³ cm⁻³ and by temperature
drop K⁻¹ for gas : 1) D₂ 2) N₂

Under these conditions, the calculated heat losses are

	power W
- pure conduction in stagnant N ₂	12
- with natural convection	80
The measured heat losses are, for the following insulations :	
- 4 screens dividing the 20 mm gas gap in five gaps of 6, 5, 4, 3 and 2 mm (from 300 K to 80 K)	19
- glass wool $\rho = 0.035 \text{ g cm}^{-3}$	15
- alumina wool $\rho = 0.12 \text{ g cm}^{-3}$	19
- graphite wool $\rho = 0.1 \text{ g cm}^{-3}$	29
- no insulation	40 - 50

These very rough experiments show that the heat losses, without any internal heating, but with materials which prevent full natural convection, are higher than the calculated ones for ideal stagnant gas by a factor of :

1.5 for screens

2.8 for graphite wool

(more than 4 without any insulating material).

5. CONCLUSIONS

The present calculations and preliminary experiments show that heat losses through a D₂ gas gap would be higher than those for an ideally stagnant gas (pure conduction : heat flux $.1 \text{ watt cm}^{-1}$ thus, .5 Kw for a 5000 cm^2 source surface), but that they would remain limited to 2 Kw (no insulation) and maybe to 1 Kw with optimum insulation.

They are acceptable if the "thin" magnesium technics without vacuum instead of the conventional "thick" aluminium technics with vacuum, could reduce from 25 to 10 Kw, the total nuclear heating of a large deuterium cold source in a reactor with flux and power 5 times higher than that of the ILL reactor.

An Alternative in the Heat Transfer Design: A Cold Neutron Source Without Vacuum Insulation

Paul Ageron

Questions/Answers/Comments

(E. Ottewitte)

Question:

What is the composition of the thin Mg layer?

Answer:

(Audience) 3% Al, 1% Zn

(C. West)

Comment:

This idea is clearly aimed at the Advanced Neutron Source, and we are very grateful for it. Dr. Ageron has helped us many times before, also. We will explore this idea with Dr. Ageron.

THE ORNL LIQUID NITROGEN SIMULATION FACILITY

Cliff Eberle
Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

The ANS cold neutron sources will experience more severe operating conditions than do existing cold sources. A liquid nitrogen simulation facility is being built to address the issues raised by operating at conditions not previously experienced. This paper discusses the ANS cold source heat loading, explains why liquid nitrogen was chosen as the simulant, describes the simulation facility, and discusses planned tests with test objectives.

I. INTRODUCTION

The Advanced Neutron Source (ANS) is an experimental facility to be built at Oak Ridge National Laboratory (ORNL). A primary objective of the ANS Project is to design and construct the world's best research reactor for neutron scattering¹. The production of "cold" neutrons, with wavelengths longer than 4 Angstroms (energy < 0.005 eV) is crucial to accomplishing this objective. Two identical, deuterium-moderated cold neutron sources will produce the required cold neutron flux.

Thermal performance must be assured in the ANS cold neutron sources. Good thermal performance will be achieved when the following conditions are met:

1. The "local" and mean pool liquid fractions equal or exceed a specified minimum value;
2. The liquid level equals or exceeds a specified minimum value;
3. Stable operation is maintained, i.e., the operator can control pool behavior with no geysering, flow blockages or reversals, "ratcheting" between flow regimes, etc.

The ANS cold neutron sources will experience substantially more severe normal operating conditions than does any existing cold source. Table I shows the comparison of the projected operating conditions for the ANS cold sources with those of the Institute Laue-Langevin (ILL) vertical cold source, which experiences the most severe operating conditions among existing cold sources.

TABLE I
COMPARISON OF ANS* AND ILL CNS OPERATING CONDITIONS

	<u>ANS</u>	<u>ILL</u>
Total heat load ⁺	20	5.8
Heat evacuated by moderator	10	5.8
Structural heat load	10	2.7
Internal heat load	10	3.1
Thermal neutron flux [#]	4.6	0.6

*PS-2 reference core, unperturbed at nominal power level

⁺All heat loads in units of kW

[#]Flux in units of 10^{19} neutrons $m^{-2} s^{-1}$

The ILL cold source has performed quite well, and experiments showed that it should continue to perform well to a heat loading of at least 9 kW².

Examination of Table I shows two striking differences between the ANS and ILL cold sources that will affect the thermal-hydraulics; the heat load evacuated by the moderator is substantially greater in the ANS than at ILL, and little or none of the structural heating is evacuated by the moderator in the ANS, hence the bubble dynamics will be different. Therefore an experimental Characterization Test Article, which uses liquid nitrogen (LN₂) as a moderator simulant, is being built at ORNL to address the following issues:

1. The thermal-hydraulics at the projected ANS heat loads are unknown.
2. The effects of wall heat flux to the moderator are unknown.
3. The effects of vessel geometry are unknown.
4. The operating limits are unknown.

II. COLD SOURCE DESCRIPTION

The cold source cryostats will be vacuum-jacketed, with the cold source centers located approximately 700 mm radially from, and at the same elevation as, the reactor core center. The baseline cold source geometry is a 380 mm diameter sphere, similar to the ILL vertical cold source; however, other configurations which may perform better at the higher ANS heat loads are under investigation. A very cold neutron (VCN) guide will penetrate each cold source with a window between the guide and the moderator. The VCN guides must therefore be included in the pressure boundaries. All of the cold neutron guides will terminate approximately one meter from the cold sources and therefore will not affect their pressure boundaries.

The cold source walls will be independently cooled by gaseous helium. The internally deposited moderator heat load cannot be removed by wall cooling alone, so it will be removed by a helium-cooled, reflux condenser located above each cold source. Deuterium will be transported between the cold sources and the condensers in concentric tubes, with

central liquid return and annular vapor exhaust to minimize the heat load on the liquid return lines.

Figure 1. ANS Reactor Assembly Elevation View

Figure 1 shows one cold source assembly installation in a cutaway view of the reactor area, and Figure 2 shows the cold source locations in a plan view.

Figure 2. ANS Reflector Tank Plan View

III. BASIS FOR SIMULATING WITH LN_2

The simulant fluid properties or relevant dimensionless ratios should be similar to those of liquid deuterium. In addition, the simulant should be inexpensive and readily available while posing minimum safety hazards. Water would be the preferred simulant if it could be shown to reasonably well simulate deuterium behavior.

Some important parameters include the bubble velocity, equation (1)³, the volume vapor generation, equation (2), and the dimensionless velocity, equation (3).

$$U_b = 1.53 \left[\frac{9 \sigma \Delta \rho}{\rho_L^2} \right]^{1/4} \quad (1)$$

$$G = \frac{1}{\rho_v L} \quad (2)$$

$$U^* = \frac{\dot{Q}_v H_0}{\rho_v L \left[\frac{9 \sigma \Delta \rho}{\rho_L^2} \right]^{1/4}} \quad (3)$$

The dimensionless velocity has been used to correlate data by the ILL team² and in other relevant works^{4,6}. Table II compares the calculated values for several fluids at a typical ANS heat loading and pool depth. Deuterium properties are read at 0.15 MPa, the expected operating pressure in the ANS cold sources, while simulant properties are read at 0.10 MPa, which is a convenient pressure for simulation. Nitrogen and oxygen are the best simulants according to this criterion; oxygen was rejected because of safety hazards.

Table II
IMPORTANT PARAMETERS FOR DEUTERIUM AND CANDIDATE SIMULANTS*

<u>Fluid</u>	<u>Volume Vapor Generation liter/kJ</u>	<u>Bubble Velocity mm/s</u>	<u>Dimensionless Velocity</u>
Parahydrogen	2.01	194	1.98
<i>Deuterium</i>	<i>1.06</i>	<i>168</i>	<i>1.21</i>
<i>Nitrogen</i>	<i>1.09</i>	<i>156</i>	<i>1.34</i>
Argon	1.07	144	1.43
Oxygen	1.05	158	1.28
Methane	1.08	206	1.01
Ethane	1.00	194	0.99
Propane	0.97	192	0.96
Water (H ₂ O)	0.74	240	0.59

*Saturated simulant fluid properties read at 0.10 MPa pressure, deuterium at 0.15 MPa pressure. Assumed heat load is 10 kW, nonboiling pool depth is 300 mm.

Further calculations were performed to verify the choice of nitrogen as the simulant. Single bubble dynamics calculations were performed based on the correlations developed by Forster and Zuber^{7,8} and Peebles and Garber⁹. Figures 3 through 5 show sample calculations for 0.5 K liquid superheat. Note the excellent similarity of the single bubble dynamics for deuterium and nitrogen.

Fig. 3 Bubble radius - time curves at 0.5 K superheat; deuterium at 0.15 MPa, nitrogen at 0.10 MPa

Fig. 4 Bubble velocity - time curves at 0.5 K superheat; deuterium at 0.15 MPa, nitrogen at 0.10 MPa

Fig. 5 Bubble position - time curves at 0.5 K superheat; deuterium at 0.15 MPa, nitrogen at 0.10 MPa

Finally, the void fraction was calculated for deuterium, nitrogen, and water in a 300 mm diameter cylindrical boiling pool with a vertical axis and surface heating from the bottom according to the method of Kataoka and Ishii¹⁰. This method cannot be used to calculate the void fraction in the ANS cold source, since it neglects the bubble nucleation and growth in the bulk liquid volume, but it is useful for comparing the fluids' behavior at specified conditions. Figure 6 shows a plot of void fraction as a function of the total heat

Fig. 6 Void fraction vs. heat load for a 300 mm diameter cylindrical vessel with surface heating from the bottom

load. Note that again the results for deuterium and nitrogen are nearly identical, while the water results are quite dissimilar to the deuterium results.

IV. CHARACTERIZATION TEST ARTICLE DESCRIPTION

The main components of the Characterization Test Article are shown in Figure 7. Structural supports are not shown. The test vessel is a 330 mm diameter spherical glass flask. Heater wires distributed throughout the test vessel simulate the internal nuclear heating. Flexible heating elements epoxied to the vessel's surface simulate a specified wall heat flux into the moderator; a clear viewing area is maintained between adjacent heaters. To enhance process observation, adiabatic wall testing can be conducted before the wall heaters are installed. The test vessel assembly is submersed in a LN₂ bath to prevent uncontrolled surface heating. Large diameter viewports in the bath dewar walls allow the

Fig. 7 Simulation facility main hardware

Fig. 8 Internal heater subassembly

experimenters to light, observe, control, and photographically record events in the test vessel. A head dewar which sits directly above the bath dewar supplies liquid to the test vessel. A regulating valve submersed in the head dewar controls the liquid flowrate to the test vessel. The regulating valve can be motor driven or manually operated. A flexible shaft (not shown) connects the dewar cover feedthrough and the motor or operator.

A detail of the internal heater assembly in the test vessel is shown in Figure 8. The test vessel is split at the horizontal midplane to facilitate heater installation. After the heaters are placed in the vessel, a stainless steel fixturing ring is placed

Fig. 9. Test vessel subassembly

between the hemispheres, A+B putty is applied in the joints, and the hemispheres are clamped together as illustrated in Figure 9. The heaters are made from 1 mm diameter Chromel wire wound around insulating bobbins machined from G-10 rod. The heating assembly contains two heaters at each of four vertical positions for a total of eight independently controlled heaters. The total length of heater wire is 17.5 meters, hence approximately 10 kW of power can be applied in liquid nitrogen's nucleate boiling regime. This is not believed to be a thermal-hydraulics limit, but possibly a structural limit. The wires will become quite hot in film boiling and may sag enough due to thermal expansion-induced loss of tension to develop an electrical short circuit.

Fig. 10 Piping and instrumentation diagram

The piping and instrumentation are depicted in Figure 10. Liquid is supplied from a 42,000 liter dewar. A K-bottle of high pressure gas is used to pressurize the head dewar ullage space as necessary. Pressures and flowrates can be controlled by operation of the valves in the piping system. The test vessel liquid level will be monitored visually and controlled by the facility operator. An ultrasonic densitometer will be tested as a liquid

level gage, and subsequently used for that purpose if it performs satisfactorily. The test vessel pressure will be monitored by an absolute pressure transducer. Type E thermocouples will monitor temperatures at the test vessel wall, in the test liquid and ullage spaces, and in the bath liquid. Heater power input is measured by standard power meters.

V. PLANNED TESTS

The planned tests and objectives are described below. They are summarized in Table III.

A. Liquid Level

A specified liquid level must be maintained to moderate the neutrons entering the cold guides, hence liquid level is a very important parameter. The objectives of the liquid level experiments are to prove that the liquid level is controllable, to determine the critical heat load, and to measure the liquid level at specified operating conditions. The liquid level will be determined by visual observation through a window. In addition, an ultrasonic densitometer, described in ref. [11], will be tested for use as a level sensor in a bubbling pool of cryogenic liquid. It has already been successfully tested in a quiescent LN₂ pool¹².

B. Two-phase Density

Neutron thermalization is greatly influenced by the liquid fraction or two-phase density. The R&D program must demonstrate that an acceptably high two-phase density can be maintained at all normal operating conditions, and that it can be estimated with reasonable accuracy for abnormal conditions. The objective of the two-phase density experiments is to determine the two-phase density at specified operating conditions. The density will be determined by the ultrasonic densitometer.

Table III
TESTS AND OBJECTIVES

<u>Tests</u>	<u>Objectives</u>
Liquid level	<ul style="list-style-type: none"> -prove controllability -determine critical heat load -measure at specified operating conditions
Two-phase density	<ul style="list-style-type: none"> -measure at specified operating conditions
Heated wall	<ul style="list-style-type: none"> -compare thermal performance to adiabatic wall condition -determine optimum heating rate
Cooled wall	<ul style="list-style-type: none"> -compare thermal performance to adiabatic wall condition -determine optimum cooling rate
Liquid return configuration	<ul style="list-style-type: none"> -determine how fill tube geometry affects thermal performance
Vent geometry/vapor separation techniques	<ul style="list-style-type: none"> -determine liquid entrainment effects -determine how to minimize liquid entrainment
Nucleation site enhancement	<ul style="list-style-type: none"> -determine the effect of adding bubble nucleation sites
Controlled superheat tests	<ul style="list-style-type: none"> -compare events at uniform liquid superheat to those with distributed wire heaters
Vessel geometry/volume	<ul style="list-style-type: none"> -compare different cold source geometries -test the final design vessel geometry

C. Heated Wall

The wall heat flux can be controlled by varying the helium flowrate and/or inlet state. A heated wall will contribute two heat transfer mechanisms that will affect system stability. First, natural convection would be established. Second, surface boiling will occur. These are the expected results: (1) convection currents will circulate cooler liquid into the bulk

volume of the vessel, which helps to remove the volumetrically deposited heat and to minimize the liquid superheat, and (2) incipient boiling will occur at a lower liquid superheat, which can prevent the occurrence of sudden and violent boiling. The objectives of the heated wall tests are to determine if thermal performance is improved relative to that of an adiabatic wall condition, and if so to determine the optimum heating rate. This will be accomplished by repeating the tests of sections A and B with wall heaters on.

D. Cooled Wall

A cooled wall might help to stabilize the system in a similar manner to a heated wall. However, any benefit would derive from natural convection, because surface boiling would not occur. The convection currents are expected to circulate in a pattern roughly opposite that of the heated wall. The objective of the cooled wall tests are to determine if thermal performance is improved relative to that of an adiabatic wall condition, and if so, to determine the optimum cooling rate. This will be accomplished by repeating the tests of sections A and B with the liquid in the test vessel at an elevated pressure. Hence the saturation temperature of the test liquid will exceed the bath temperature, and wall cooling will result.

E. Liquid Return Configuration Study

The characterization test article is designed with a removable tip for liquid return on the fill tube. Various tip designs (e.g., perforations or differing lengths) may be attached to study the effects of fill tube geometry. The objective of the liquid return configuration study is to determine how the fill tube geometry affects the system's thermal performance. The tests of sections A and B will be repeated with various tips attached to the fill tube.

F. Vent Geometry and Vapor Separation Techniques

At high heat loads, two-phase flow will exist near the liquid-vapor interface, and perhaps well into the exhaust annulus. The vent geometry was shown by ILL experiments to be an important design parameter that affects the two-phase density in the cold source¹³. Various vent geometries will be evaluated to determine a configuration that will provide stability at all thermal loading conditions. A screen or other device may be required to separate the vapor from the entrained liquid. The objective of these experiments are to determine if enough liquid entrainment occurs to be detrimental, and if so how to prevent it. The tests of sections A and B will be repeated for different vent geometries.

G. Nucleation Site Enhancement Study

The liquid superheat may become too high before incipient boiling occurs. Sudden and violent boiling might then occur, resulting in system instability. The addition of artificial bubble nucleation sites, heated by radiation in the real cold source, may lower the bulk liquid superheat, thus enhancing the system stability. The objective of this test is to determine if adding artificial nucleation sites improves the system stability. The tests of sections A and B will be repeated with artificial nucleation sites in the test vessel.

H. Controlled Superheat Tests

A deficiency in the tests of sections A-G is their inability to simulate a uniform superheat distribution. Uniform superheat may be achieved by temporarily raising the test liquid pressure, allowing the liquid to warm almost to its new saturation temperature, and then depressurizing. The objective of this test series is to determine if the tests of sections A-G simulate reasonably well what happens under uniform liquid superheat conditions.

This method cannot simulate a steady state heat load; boiling will be transient. This presents only a minor obstacle, however. There is vast experience addressing such events, because this experiment is quite similar to bubble chamber operation.

I. Vessel Geometry and Volume

The geometry and volume of the cold source are expected to strongly influence the system's thermal performance. The LN₂ test facility has been designed to accommodate multiple test vessel geometries. As the cold source design evolves, the latest cold source geometry can be tested in the LN₂ test facility.

VI. CONCLUSIONS

The ANS cold sources will be operated beyond previously experienced conditions, resulting in the potential for significant problems and a need for experimental confirmation of analytical models. A liquid nitrogen simulation facility is being built for this purpose. Liquid nitrogen was shown to excellently simulate liquid deuterium behavior. The planned tests as described should provide the necessary information.

VII. ACKNOWLEDGEMENTS

The author thanks L. D. Golden and K. W. Buchanan for their assistance in preparation of the manuscript, tables, and figures, and T. L. Ryan, D. L. Selby, and C. D. West for their technical assistance.

Work performed at Oak Ridge National Laboratory, operated for the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

VIII. REFERENCES

1. C. D. West, "The U.S. Advanced Neutron Source", Proc. 10th Mtg. Intl. Collaboration Advanced Neutron Sources (ICANS X), Los Alamos, NM, 643 (October 1988).
2. P. Ageron and J. M. Astruc, private communication (1989).
3. T. Z. Harmathy, "Velocity of Large Drops and Bubbles in Media of Infinite or Restricted Extent", AIChE J., 6, 2, 281 (1960).
4. M. Epstein, "Transient Behavior of a Volume-Heated Boiling Pool", paper 75-WA/HT-31, presented at ASME Winter Mtg., Houston, TX (1975).
5. M. S. Kazimi and J. C. Chen, "Void Distribution Boiling Pools with Internal Heat Generation", Nucl. Sci. Engr., 65, 17 (1978).
6. T. Ginsberg, O. C. Jones, Jr., and J. C. Chen, "Flow Dynamics of Volume-Heated Boiling Pools", ASME paper 79-HT-102, presented at ASME/AIChE 18th Nat'l Heat Transfer Conf., San Diego, CA (August 1979).
7. H. K. Forster and N. Zuber, "Growth of a Vapor Bubble in a Superheated Liquid", J. Applied Physics, 25, 4, 474 (1954).
8. H. K. Forster and N. Zuber, "Dynamics of Vapor Bubbles and Boiling Heat Transfer", AIChE J., 1, 4, 531 (1955).
9. F. N. Peebles and H. J. Garber, "Studies on the Motion of Gas Bubbles in Liquids", Chem. Engr. Progr., 49, 2, 88 (1953).
10. I. Kataoka and M. Ishii, "Drift Flux Model for Large Diameter Pipe and New Correlation for Pool Void Fraction", Int. J. Heat Mass Transfer, 30, 9, 1927 (1987).
11. W. B. Dress, "A High Resolution Ultrasonic Densitometer", Proc. IEEE Ultrasonics Symp., 287 (Oct.-Nov. 1983).
12. L. C. Oakes, private communication (1989).
13. H. Hoffman and J. M. Astruc, "Evaluation Experimental du Taux de Remplissage en Deuterium Liquide de la Cellule Moderatrice de la SFH," ILL Report Re 972 N (p) 009 (Oct. 1983).

IX. NOMENCLATURE

G volume of vapor generation per unit heat input

g gravitational acceleration

H_o nonboiling pool depth

L latent heat of vaporization

$\dot{Q}_v$ heat load per unit volume of liquid

U_B diameter-independent, terminal bubble velocity

U^* dimensionless velocity, eq. (3)

$\Delta\rho$ density difference, $\rho_L - \rho_v$

ρ_L liquid density

ρ_v vapor density

σ surface tension

The ORNL Liquid Nitrogen Simulation Facility

Cliff C. Eberle

Questions/Answers/Comments

(P. Egelstaff)

Question:

Can you expand on the suggestion of using an electron beam target to heat the nitrogen with γ 's?

Answer:

The concept is to generate bremsstrahlung gammas by firing a particle beam (electron or neutral) into a target and to heat the test liquid with the gammas. At this time, we've performed no serious work on this concept. My intuition is that it will be very difficult, but it is the only concept for volumetrically heating a cryogen to the Advanced Neutron Source loads, which we think might be made to work at all. Acknowledgement: This idea was first suggested by Jack Carpenter of Argonne National Laboratory.

(C. West)

Comment:

We will share the cold-source test results and welcome suggestions or requests for additional experiments. Nucleation sites could be deliberately introduced into bubble chambers if our simulations (which invariably have nucleation sites) show a desirable performance.

(J. Verdier)

Question:

If the plant is operated at a pressure slightly higher than atmospheric pressure, it could probably improve the simulation between LD₂ and LN₂. Could it not?

Answer:

This statement is true, and if we can maintain a slightly elevated pressure, we may try this. However, the bath dewar cannot be operated at an elevated pressure due to structural limits. The seal at the horizontal midplane of the test vessel is a poor one; hence, some test liquid leakage would probably occur. In addition, since raising the test liquid pressure will also raise the saturation pressure, a cooled wall-boundary condition will result. Hence, adjusting the test liquid pressure may cause operational problems that do not justify the improvement in simulation of fluid dynamics.

(K. Gobrecht)

Question:

How do you simulate a wall temperature lower than the bulk liquid temperature in the vessel?

Answer:

Slightly elevate the test liquid pressure, thus its saturation temperature. This may cause operational problems as explained in the answer to J. Verdier's question.

(C. Eberle)

Comment:

Tests and calculations performed since the workshop indicate that the midplane seal integrity can be maintained only at low (for example, 7-10 Pa range) pressure elevation. This is insufficient to substantially improve the fluid dynamics simulation.

Session IV

COLD SOURCE DESIGN CONSIDERATIONS (Part II)

Chairman

Helmut Hoffman

Materials for Cold Neutron Sources: Cryogenic and Irradiation Effects

David J. Alexander

Oak Ridge National Laboratory
Metals and Ceramics Division
Oak Ridge, Tennessee USA

ABSTRACT*

Materials for the construction of cold neutron sources must satisfy a range of demands. The cryogenic temperature and irradiation create a severe environment. Candidate materials are identified and existing cold sources are briefly surveyed to determine which materials may be used. Aluminum- and magnesium-based alloys are the preferred materials. Existing data for the effects of cryogenic temperature and near-ambient irradiation on the mechanical properties of these alloys are briefly reviewed, and the very limited information on the effects of cryogenic irradiation are outlined. Generating mechanical property data under cold source operating conditions is a daunting prospect. It is clear that the cold source material will be degraded by neutron irradiation, and so the cold source must be designed as a brittle vessel. The continued effective operation of many different cold sources at a number of reactors makes it clear that this can be accomplished.

*Research sponsored by the Division of Materials Sciences, U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

I. INTRODUCTION

A cold neutron source presents a unique set of demands for the material of construction. In addition to the extremely low temperatures at which the cold source operates, an intense flux of neutrons will be present. The combination of these factors results in a very severe environment. This paper provides a survey of the materials that might be used in construction of a cold source, and outlines some of the problems that may arise. In addition, existing cold sources are briefly surveyed, and the materials used in these cold sources are described. Finally, the most promising candidate materials are identified, and some potential problems are mentioned.

II. MATERIAL REQUIREMENTS

The requirements for a structural material for a cold neutron source are severe. First and foremost, the material must allow the passage of neutrons into and out of the cold source. Any absorption of neutrons will degrade the efficiency of the device. The material must withstand the stresses imposed, which will vary depending on the design of the cold source. This problem is exacerbated by the very low temperatures at which the cold source operates, and the thermal cycles which may occur during long term operation. In order to minimize the demands on the refrigeration system the cold source material should have a low heat generation rate due to irradiation and a high thermal conductivity. The material must be compatible with the cold source moderator. The material should be readily available, and preferably relatively inexpensive. Construction of the cold source vessel demands that the material be readily fabricated, which may entail welding of relatively thin sheets. Forming and welding must not have adverse effects on the mechanical properties. The resultant structure must be leak- and vacuum-tight. Finally, other safety issues such as flammability and accident scenarios must be addressed. The result is a demanding set of design constraints.

The paramount importance of low neutron absorption eliminates several classes of alloys, including iron-, copper-, nickel-, and titanium-based alloys. Zirconium-based alloys suffer from

low thermal conductivity, making them unattractive. As a result of this process of elimination, aluminum- and magnesium-based alloys are the apparent candidate materials.

III. EXISTING COLD SOURCES

A brief survey of existing cold sources⁽¹⁻⁵⁾ is given in Table I. For comparison, the planned Advanced Neutron Source (ANS) Reactor at Oak Ridge will operate at 350 MW and the cold source will be exposed to a thermal flux of 4×10^{19} neutrons/(m²·s). In Table II the materials used for these cold sources and additional comments are listed⁽¹⁻⁹⁾. These tables indicate that aluminum alloys are the most common choice. Both 5000- and 6000-series alloys have been used successfully. Magnesium alloys have been used also.

TABLE I. EXISTING COLD SOURCES

Reactor	Reactor Power (MW)	Thermal Flux [n/(m ² ·s)]	Moderator			
			Type	Thickness (mm)	Volume (L)	Heat removed (W)
HFR Grenoble	57	6×10^{18}	LD ₂	380	25	5000
HFBR Brookhaven	60	3×10^{18}	LH ₂ subcooled	66	1.35	600
Orphee Saclay	14	3×10^{18}	LH ₂	50		500
FRJ2 Julich	15	9×10^{17}	LH ₂ + LD ₂	55	0.85	1000
DR3 Riso	10	7×10^{17}	H ₂ supercritical	60	0.57	620
FR2 Karlsruhe	43	5×10^{17}	LH ₂	45	0.25	50
EL3 Saclay	17	5×10^{17}	LH ₂	70	0.40	80
DIDO Harwell	15	4×10^{17}	LH ₂	30	0.20	40
Herald Aldermaston	5	1×10^{17}	LH ₂ + LD ₂	190	3	200
RRI Kyoto			LH ₂	154	4	70
NBSR NIST			D ₂ O/H ₂ O ice	330	30	

TABLE II. MATERIALS USED IN EXISTING COLD SOURCES

Reactor	Material	Comments
HFR Grenoble	Pure aluminum Zircaloy 2	Commercial purity; inner vessel Outer containment
HFBR Brookhaven	6061-T4 Al	Heat treated after brazing assembly
Orphee Saclay	A286	Fe-26Ni-15Cr stainless steel
FRJ-2 Julich	5052 Al	Electron beam welded, also used for vacuum jacket
DR3 Riso	5052-O Al	Limit 4.5×10^{26} n/m ² , $\approx$ 20 years Outer containment also
EL3 Saclay	5052 Al	
DIDO Harwell	Magnesium	
Herald	5056 Al	Also for vacuum chamber
RRI Kyoto	5052 Al	
NBSR NIST	AZ31B Mg	Limited by existing refrigeration

IV. ALUMINUM ALLOYS

Material Description and Cryogenic Properties

There are several classes of aluminum alloys to consider. However, only the 5000- and 6000-series alloys are feasible candidates. The 2000-series (Al-Cu) has low toughness at cryogenic temperatures, the 3000-series (Al-Mn) has low strength, and the 7000-series (Al-Zn-Mg-Cu) has poor ductility and toughness at cryogenic temperatures. The 5000-series (Al-Mg) is used extensively for cryogenic applications. These non-heat-treatable alloys are readily weldable. They have relatively low strength but high toughness over all cryogenic temperatures. The 5052 alloy contains 2.5 wt % Mg and 0.25 wt % Cr. Other possibilities include 5154 (3.5Mg-0.25Cr), 5456 (5.1Mg-0.12Cr-0.8Mn) and 5083 (4.4Mg-0.15Cr-0.7Mn). The 6000-series alloys (Al-Mg-Si) are also widely used in cryogenic applications. These medium-strength

alloys are heat-treatable with strengthening provided by the precipitation of Mg_2Si particles in the matrix, and can be welded; although a postweld heat treatment is necessary if the weld joint is to match the strength of the precipitation-hardened base metal. Possible alloys include 6061 (1.0Mg-0.6Si-0.28Cu-0.20Cr) and 6063 (0.7Mg-0.4Si).

The cryogenic properties of these alloys are well-documented, particularly for 6061. Data are available from a number of handbooks and other sources⁽¹⁰⁻¹³⁾. The tensile properties⁽¹⁴⁻¹⁶⁾ of 6061-T6, the peak strength condition for this alloy, are shown in Fig. 1. The properties of 5456-H321 are shown in Fig. 2 for comparison^(16,17). The yield strength and ductility of these alloys tends to increase as the temperature is lowered. The high values of the notched-tensile

Fig. 1. Tensile properties vs temperature for 6061-T6 aluminum. Stress concentration factor for notched tensile specimens is $K_t = 8.0$ or 6.3 . **Sources:** W. Weleff, H. S. McQueen, and W. F. Emmons, "Cryogenic Tensile Properties of Selected Aerospace Materials," pp. 14-25, and J. L. Christian and J. F. Watson, "Mechanical Properties of Several 2000 and 6000 Series Aluminum Alloys," pp. 63-76 in *Advances in Cryogenic Engineering*, Vol. 10, Proceedings of the 1964 Cryogenic Engineering Conference, K. Timmerhaus, Ed., Plenum, New York, 1965; and M. P. Hanson, G. W. Stickley, and H. T. Richards, "Sharp-Notch Behavior of Some High-Strength Sheet Aluminum Alloys and Welded Joints at 75, -320, and 423°F," p. 3 in *Symposium on Low-Temperature Properties of High-Strength Aircraft and Missile Materials*, ASTM STP 287, American Society for Testing and Materials, Philadelphia, 1961.

Fig. 2. Tensile properties vs temperature for 5456-H321 aluminum. Stress concentration factor for notched tensile specimens is $K_t = 16$. **Sources:** M. P. Hanson, G. W. Stickley, and H. T. Richards, "Sharp-Notch Behavior of Some High-Strength Sheet Aluminum Alloys and Welded Joints at 75, -320, and 423°F," p. 3 in *Symposium on Low-Temperature Properties of High-Strength Aircraft and Missile Materials*, ASTM STP 287, American Society for Testing and Materials, Philadelphia, 1961; and J. G. Kaufman, K. O. Bogardus, and E. T. Wanderer, "Tensile Properties and Notch Toughness of Aluminum Alloys at -452°F in Liquid Helium," p. 294 in *Advances in Cryogenic Engineering*, Vol. 13, Proceedings of the 1967 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1968.

data indicate that these alloys are not notch-sensitive, which suggests that they will have good toughness. A comparison of the ratio of the notched tensile strength to the yield strength as a function of the yield strength at 4 K for a number of aluminum alloys is shown in Fig. 3. The 5000- and 6000-series alloys⁽¹⁸⁾ are used for cryogenic applications because of their high notch-yield ratios.

The toughness of these alloys has been examined with notched tensile, tearing, and plane strain fracture toughness testing. The energy required for tearing of thin sheet specimens of 6061-T6 and 5456-H321 is shown⁽¹⁹⁾ in Fig. 4. These data indicate that the toughness of the 6061 material actually increases as the temperature is reduced, and the toughness of the 5456 material is relatively constant. It should be noted that the fracture toughness of 6061-T6 (Fig. 5) is much lower than one might expect from the notched tensile and tear test data^(20,21).

Fig. 3. Notch-yield ratio vs tensile yield strength for aluminum alloys at 4 K. Stress concentration factor for notched tensile specimens is $K_t = 16$. **Source:** J. G. Kaufman and E. T. Wanderer, "Tensile Properties and Notch Toughness of Some 7XXX Alloys at -452°F ," p. 27 in *Advances in Cryogenic Engineering*, Vol. 16, Proceedings of the 1970 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1971.

Fig. 4. Tear resistance of 6061-T6 and 5456-H321 at low temperatures. **Source:** J. G. Kaufman and M. Holt, "Evaluation of Fracture Characteristics of Aluminum Alloys at Cryogenic Temperatures," pp. 77-85 in *Advances in Cryogenic Engineering*, Vol. 10, Proceedings of the 1964 Cryogenic Engineering Conference, K. Timmerhaus, Ed., Plenum, New York, 1965.

However, these fracture toughness data are for thick sections only, and material in a thin-walled cold source should have a higher toughness, since fracture would occur under plane-stress conditions.

These aluminum alloys are readily weldable under appropriate conditions. The mechanical properties of welds have been studied at cryogenic temperatures by several investigators^(10,11,16,22-24).

Effects of Radiation

The effects of irradiation on these alloys have been studied to some extent. Limited data are available for irradiations slightly above room temperature on 6061, 6063, 5052 and 5154 alloys⁽²⁵⁻³²⁾. These data indicate that the yield and ultimate strengths are increased by

Fig. 5. Plane-strain fracture toughness of 6061-T6 at low temperatures. **Source:** F. G. Nelson and J. G. Kaufman, "Plane Strain Fracture Toughness of Aluminum Alloys at Room and Subzero Temperatures," pp. 27-39 in *Fracture Toughness Testing at Cryogenic Temperatures*, ASTM STP 496, American Society for Testing and Materials, Philadelphia, 1971.

irradiation whereas the ductility is greatly reduced. Data^(27,31) for 6061-T6 and 5052-0 are shown in Figs. 6 and 7, respectively. The primary mechanism for these changes is the production of silicon transmuted from the aluminum matrix by thermal neutrons. In unalloyed aluminum and in 6061-T6, the silicon forms tiny particles of elemental silicon in the matrix, resulting in increased strengths. In the 5000-series alloys the silicon reacts with magnesium in solution to form precipitates of Mg_2Si . Thus, the 5000-series alloys may be more greatly affected than quenched-and-tempered 6000-series alloys, which do not have excess magnesium present in the matrix. Since thermal neutrons are responsible for the silicon generation, the thermal neutron flux may play a greater role in embrittlement than the fast neutron flux^(25,28,31), at least at temperatures where migration of silicon can occur. Generation of point defects by the fast neutrons will increase the mobility of the silicon. Above room temperature, point defects are mobile in aluminum, and the majority are annihilated by recombination. However, these diffusional processes will be severely curtailed at the low temperatures at which the cold source will operate. Under such conditions, point defects and transmuted silicon atoms will be frozen-in, and the degree of hardening per unit flux may be much greater than at high temperatures. This is evident in the very limited cryogenic irradiations of aluminum alloys that have been carried out⁽³³⁻³⁶⁾ to a maximum fast fluence of only 10^{21} neutrons/m² at 16 K for 6061-T6 and 5456-H321. The yield strength at 16 K of the 6061 alloy increased from 330 MPa unirradiated to 390 MPa after irradiation whereas the 5456 alloy showed a much greater increase (from 300 to 460 MPa). Irradiations to these low fluences at 60°C would cause no change in yield strength^(27,31,32) (see Figs. 6 and 7). The ultimate tensile strengths for the 6061 and 5456 alloys were essentially unaffected (450 and 640 MPa, respectively), as was the total elongation to failure (28 and 16%, respectively). Limited tests at the Grenoble reactor⁽³⁷⁾ indicate that cryogenic irradiation results in severe embrittlement. No data exist that show the effect of irradiation by cold neutrons at either near-ambient or cryogenic temperatures.

The considerable experimental problems associated with cryogenic irradiations make such data very difficult to generate. Even warming the specimen to liquid nitrogen temperatures (77 K) will result in significant recovery, as pointed out in a review article⁽³⁸⁾. Thus, one is essentially

Fig. 6. Effect of fast fluence (>0.1 MeV) on tensile properties of 6061-T6 at 323 K. **Source:** K. Farrell and R. T. King, "Tensile Properties of Neutron-Irradiated 6061 Aluminum Alloy in Annealed and Precipitation-Hardened Conditions," pp. 440-49 in *Effects of Irradiation on Structural Materials*, ASTM STP 683, J. A. Sprague and D. Kramer, Eds., American Society for Testing and Materials, Philadelphia, 1979.

Fig. 7. Effect of fast fluence (>0.1 MeV) on tensile properties of 5052-O at 323 K. **Source:** K. Farrell, "Microstructure and Tensile Properties of Heavily Irradiated 5052-0 Aluminum Alloy," *Journal of Nuclear Materials* 97, 33-43 (1981).

forced to consider the cold source material as brittle, and design accordingly. Even with annealing treatments between cold cycles to remove the irradiation damage, the material will rapidly reembrittle.

V. MAGNESIUM ALLOYS

The magnesium alloys can be divided into two groups, those which contain zirconium, added as a grain refining agent, and those which do not. Aluminum is often added to the latter group to increase the strength. A common medium-strength alloy is AZ31B (3Al-1Zn-0.2Mn). This alloy is available in a range of sheet, plate and extrusions.

The mechanical properties at cryogenic temperatures have been measured for a number of magnesium alloys, and can be found in handbooks^(12,39). In general, the yield and ultimate tensile strengths increase as the temperature is lowered, while the ductility decreases⁽³⁹⁾ as shown for extruded AZ31B-F in Fig. 8. Limited data^(40,41) are also available for welded material.

The effect of irradiation has been studied for only a few alloys. While there has been a fair amount of work done on the Magnox alloys used in the British nuclear industry⁽⁴²⁾, other alloys have not received the same attention. Sturcken⁽³⁰⁾ irradiated a series of simple magnesium-aluminum alloys, and observed increases in the yield and ultimate strengths and very large decreases in the ductility.

The only available data for cryogenic irradiations involve basic studies of the recovery processes which accompany annealing^(43,44) and studies of the deformation of single crystals^(45,46). These studies indicate that recovery of point defects will begin at very low temperatures, as is the case for the aluminum alloys. No data exist for the effect of irradiation by cold neutrons on the mechanical properties of magnesium alloys.

Fig. 8. Tensile properties vs temperature of AZ31B-F magnesium. *Source: Metals Handbook, Ninth Edition, Vol. 2, Properties and Selection: Nonferrous Alloys and Pure Metals, p. 554, American Society for Metals, Metals Park, Ohio, 1979.*

VI. DISCUSSION

There are very limited data for the mechanical properties of possible cold source structural materials at cryogenic ($T < 25$ K) irradiation conditions. All indications are that the material will be severely embrittled as a consequence of irradiation at low temperature. However, the fact that more than ten different cold sources have been successfully built and operated indicates that the problems of material selection and safe operation are not insurmountable. A common approach seems to be the provision of a secondary containment shield which will provide an additional layer of protection for the cold source vessel in addition to vacuum thermal insulation. Because of the degradation of the mechanical properties, the cold source vessel must be considered very brittle, and must be designed accordingly. It is apparent that this can be done successfully.

The generation of mechanical properties data for cryogenic irradiation conditions is a daunting task. The difficulties associated with maintaining the very low temperatures necessary to

prevent annealing out the radiation damage during removal of the specimen from the irradiation facility are formidable. The common approach to the limited cryogenic irradiation mechanical property testing done in the past was to irradiate and test in situ using specially designed irradiation facilities. This limited the irradiation conditions to very low fluences and only relatively simple mechanical tests such as tensile or notched tensile tests could be conducted. Conducting a more complicated fracture mechanics test seems an unlikely possibility.

One avenue to consider is conducting irradiations at liquid nitrogen temperatures. It should be feasible to maintain this temperature during irradiation and subsequent transfer and testing. Although the mechanism of embrittlement at 77 K may be somewhat different than at much lower temperatures, this should be a step in the right direction. Even in this case, it may be difficult to find a facility for these irradiations.

Yield and ultimate tensile strengths can be measured with relatively simple apparatus at 77 K. Conducting a fracture mechanics test of thin sheet material will be much more difficult. The possibility of using a simple test such as a notched tensile or a tear test should be considered. This would require the development of a good correlation between the notched or tear test and the actual failure of a vessel, perhaps by conducting proof tests at 77 K by pressurizing intentionally flawed vessels. A dummy vessel could be built from an alloy with a silicon content equal to the estimated lifetime neutron-generated level of silicon. The vessel could be solution-treated to dissolve the silicon, and then quenched into liquid nitrogen to hold as much of the silicon in solution as possible, to simulate the very uniform distribution of silicon that would be produced by cryogenic irradiation. The vessel could then be tested to failure at 77 K. In any case, it seems prudent to design a cold source so that it can be removed from the reactor and replaced.

VII. SUMMARY AND CONCLUSIONS

Selection of a material for the construction of a cold neutron source requires satisfying many demanding criteria. Very little data exist for mechanical properties under irradiation conditions at low temperature. The favored material of construction appears to be either aluminum-magnesium or aluminum-magnesium-silicon alloys. These alloys offer adequate cryogenic mechanical properties in the unirradiated condition, and are readily formed and welded. The aluminum-magnesium-silicon alloys may be somewhat less sensitive to irradiation, but at cryogenic temperatures either alloy will quickly become embrittled. Generating mechanical property data for cryogenic irradiation conditions is a difficult task. Irradiation at 77 K may provide an indication of the effects, but will not fully duplicate the operating conditions. Materials under these conditions will rapidly embrittle, and thus it is necessary to consider the cold source as a brittle vessel. Despite these constraints, it is clear that it is possible to design and operate cold sources safely and effectively, as the operation of many different cold sources in many different reactors attests.

VIII. ACKNOWLEDGMENTS

I would like to thank K. Farrell for several interesting discussions concerning radiation embrittlement of aluminum alloys and a very helpful review of the manuscript. R. E. Pawel provided many of the referenced articles. The helpful responses of P. Kopetka of NIST, D. Rorer of Brookhaven National Laboratory, K. N. Clausen of Riso National Laboratory, and M. Utsuro of the Kyoto University Research Reactor Institute to inquiries about the cold sources at their respective institutions are greatly appreciated. I would like to thank G. T. Yahr, C. D. West, and D. E. McCabe for review of the manuscript and J. L. Bishop who did an excellent job preparing the manuscript.

IX. REFERENCES

1. P. Ageron, J. M. Astruc, A. Lacaze, and J. Verdier, "Cold and Ultra-Cold Neutrons: a Test Facility for Cryogenic Engineering," pp. 458-60 in *Proceedings of the Fifth International Cryogenic Engineering Conference, Kyoto 1974*, K. Mendelssohn, Ed., IPC Science and Technology Press, Guildford, Surrey, England, 1974.
2. H. Hagen and J. A. Leth, "The Design and Manufacture of a Cold-Neutron Source for the Danish Research Reactor DR 3," pp. 271-79 in *Irradiation Facilities for Research Reactors*, Proceedings of the Symposium on Irradiation Facilities for Research Reactors, Teheran, November 6-10, 1972, International Atomic Energy Agency, Vienna, 1973.
3. P. Kopetka, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, personal communication to D. J. Alexander, Oak Ridge National Laboratory, Oak Ridge, Tennessee, February 12, 1990.
4. K. N. Clausen, Riso National Laboratory, Roskilde, Denmark, personal communication to D. J. Alexander, Oak Ridge National Laboratory, Oak Ridge, Tennessee, February 13, 1990.
5. M. Utsuro, Research Reactor Institute, Kyoto University, Osaka, Japan, personal communication to D. J. Alexander, Oak Ridge National Laboratory, Oak Ridge, Tennessee, February 17, 1990.
6. P. Ageron, J. M. Astruc, D. Cribier, G. Der Nigohossian, P. Roubeau, J. P. Perves, and J. Verdier, "Les Sources de Neutrons Froids," pp. 247-59 in *Irradiation Facilities for Research Reactors*, Proceedings of the Symposium on Irradiation Facilities for Research Reactors, Teheran, November 6-10, 1972, International Atomic Energy Agency, Vienna, 1973.
7. M. C. J. Todd, "A Cold Neutron Source on a 5-MW Pool Reactor," pp. 261-69 in *Irradiation Facilities for Research Reactors*, Proceedings of the Symposium on Irradiation Facilities for Research Reactors, Teheran, November 6-10, 1972, International Atomic Energy Agency, Vienna, 1973.
8. C. Doose, F. Stelzer, H. Stiller, and A. Tholen, "Engineering Aspects of the Cold Neutron Source at the Reactor DIDO," pp. 235-46 in *Irradiation Facilities for Research Reactors*, Proceedings of the Symposium on Irradiation Facilities for Research Reactors, Teheran, November 6-10, 1972, International Atomic Energy Agency, Vienna, 1973.

9. G. Gistau and J. Verdier, "The Cold Neutron Sources of the Research Reactor Orphee at Saclay, France," pp. 359-64 in *Proceedings of the Eighth International Cryogenic Engineering Conference*, C. Rizzuto, Ed., Genova, June 3-6, 1980, IPC Science and Technology Press, Guildford, Surrey, England, 1980.
10. D. Mann, Ed., *LNG Materials and Fluids, A User's Manual of Property Data in Graphic Format*, Cryogenics Division, Institute for Basic Standards, U.S. National Bureau of Standards, Boulder, Colorado, 1977.
11. *Cryogenic Materials Data Handbook (Revised)*, AFML-TDR-64-280, Supplement 4, Vol. II, Sections D, E, F, G, H, and I, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio (August 1968).
12. *Military Standardization Handbook, Metallic Materials and Elements for Aerospace Vehicle Structures*, MIL HDBK-5D, U.S. Department of Defense, Washington, D.C., (June 1983).
13. M. F. Marchbanks, *Savannah River Laboratory Aluminum Alloys Properties Databook*, Savannah River Laboratory, Aiken, South Carolina (February 26, 1988).
14. W. Weleff, H. S. McQueen, and W. F. Emmons, "Cryogenic Tensile Properties of Selected Aerospace Materials," pp. 14-25 in *Advances in Cryogenic Engineering*, Vol. 10, Proceedings of the 1964 Cryogenic Engineering Conference, K. Timmerhaus, Ed., Plenum, New York, 1965.
15. J. L. Christian and J. F. Watson, "Mechanical Properties of Several 2000 and 6000 Series Aluminum Alloys," pp. 63-76 in *Advances in Cryogenic Engineering*, Vol. 10, Proceedings of the 1964 Cryogenic Engineering Conference, K. Timmerhaus, Ed., Plenum, New York, 1965.
16. M. P. Hanson, G. W. Stickley, and H. T. Richards, "Sharp-Notch Behavior of Some High-Strength Sheet Aluminum Alloys and Welded Joints at 75, -320, and 423°F," p. 3 in *Symposium on Low-Temperature Properties of High-Strength Aircraft and Missile Materials*, ASTM STP 287, American Society for Testing and Materials, Philadelphia, 1961.
17. J. G. Kaufman, K. O. Bogardus, and E. T. Wanderer, "Tensile Properties and Notch Toughness of Aluminum Alloys at -452°F in Liquid Helium," p. 294 in *Advances in Cryogenic Engineering*, Vol. 13, Proceedings of the 1967 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1968.
18. J. G. Kaufman and E. T. Wanderer, "Tensile Properties and Notch Toughness of Some 7XXX Alloys at -452°F," p. 27 in *Advances in Cryogenic Engineering*, Vol. 16, Proceedings of the 1970 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1971.

19. J. G. Kaufman and M. Holt, "Evaluation of Fracture Characteristics of Aluminum Alloys at Cryogenic Temperatures," pp. 77-85 in *Advances in Cryogenic Engineering*, Vol. 10, Proceedings of the 1964 Cryogenic Engineering Conference, K. Timmerhaus, Ed., Plenum, New York, 1965.
20. F. G. Nelson and J. G. Kaufman, "Plane Strain Fracture Toughness of Aluminum Alloys at Room and Subzero Temperatures," pp. 27-39 in *Fracture Toughness Testing at Cryogenic Temperatures*, ASTM STP 496, American Society for Testing and Materials, Philadelphia, 1971.
21. F. G. Nelson, P. E. Schilling, and J. G. Kaufman, "The Effect of Specimen Size on the Results of Plane-Strain Fracture-Toughness Tests," pp. 33-50 in *Engineering Fracture Mechanics*, Vol. 4, Pergamon Press, Great Britain, 1972.
22. J. G. Kaufman and E. W. Johnson, "New Data on Aluminum Alloys for Cryogenic Applications," pp. 637-49 in *Advances in Cryogenic Engineering*, Vol. 6, Proceedings of the 1960 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1961.
23. F. G. Nelson, J. G. Kaufman, and E. T. Wanderer, "Tensile Properties and Notch Toughness of Groove Welds in Wrought and Cast Aluminum Alloys at Cryogenic Temperature," pp. 71-82 in *Advances in Cryogenic Engineering*, Vol. 14, Proceedings of 1968 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1969.
24. J. L. Christian and J. F. Watson, "Mechanical Properties of Several 5000-Series Aluminum Alloys at Cryogenic Temperatures," pp. 490-99 in *Advances in Cryogenic Engineering*, Vol. 7, Proceedings of 1961 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1962.
25. R. T. King, A. Jostsons, and K. Farrell, "Neutron Irradiation Damage in a Precipitation-Hardened Aluminum Alloy," pp. 165-80 in *Effects of Radiation on Substructure and Mechanical Properties of Metals and Alloys*, ASTM STP 529, American Society for Testing and Materials, Philadelphia, 1973.
26. K. Farrell and A. E. Richt, "Postirradiation Properties of the 6061-T6 Aluminum High Flux Isotope Reactor Hydraulic Tube," pp. 311-25 in *Properties of Reactor Structural Alloys After Neutron or Particle Irradiation*, ASTM STP 570, American Society for Testing and Materials, Philadelphia, 1975.
27. K. Farrell and R. T. King, "Tensile Properties of Neutron-Irradiated 6061 Aluminum Alloy in Annealed and Precipitation-Hardened Conditions," pp. 440-49 in *Effects of Irradiation on Structural Materials*, ASTM STP 683, J. A. Sprague and D. Kramer, Eds., American Society for Testing and Materials, Philadelphia, 1979.

28. J. R. Weeks, C. J. Czajkowski, and P. R. Tichler, "Effects of High Thermal and High Fast Fluences on the Mechanical Properties of Type 6061 Aluminum on the HFBR," pp. 441-52 in *Effects of Radiation on Materials: 14th International Symposium (Volume II)*, ASTM STP 1046, N. H. Packan, R. E. Stoller, and A. S. Kumar, Eds., American Society for Testing and Materials, Philadelphia, 1990.
29. E. F. Sturcken, C. W. Krapp, G. B. Alewine, "Effects of Irradiation on 6063 Aluminum Structural Components," *Nuclear Metallurgy* 19, 103-32 (1973).
30. E. F. Sturcken, "Irradiation Effects in Magnesium and Aluminum Alloys," *Journal of Nuclear Materials* 82, 39-53 (1979).
31. K. Farrell, "Microstructure and Tensile Properties of Heavily Irradiated 5052-0 Aluminum Alloy," *Journal of Nuclear Materials* 97, 33-43 (1981).
32. E. Lijbrink, H. J. van Grol, F. Dekker, and W. van Witzenburg, "Effects of Neutron Irradiation on the Mechanical Properties of a 5154-0 Type Aluminum Alloy," pp. 765-78 in *Effects of Radiation of Materials: Eleventh Conference*, ASTM STP 782, H. R. Brager and J. S. Perrin, Eds., American Society for Testing and Materials, Philadelphia, 1982.
33. C. A. Schwanbeck, *Effect of Nuclear Radiation on Materials at Cryogenic Temperatures*, NASA CR-54881, LAC ER-8434, National Aeronautics and Space Administration Lewis Research Center, Cleveland, January 1965.
34. E. T. Smith, "Measuring the Combined Effects of Nuclear Radiation and Cryotemperatures on the Tensile and Shear Properties of Materials," pp. 478-85 in *Advances in Cryogenic Engineering*, Vol. 11, Proceedings of the 1965 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1966.
35. W. Weleff, "Radiation Effects on Shear Strength of Several Alloys at Liquid Hydrogen Environment," pp. 544-56 in Vol. 12, Proceedings of the 1966 Cryogenic Engineering Conference, K. D. Timmerhaus, Ed., Plenum, New York, 1967.
36. J. J. Lombardo, C. E. Dixon, and J. A. Begley, "Cryogenic Radiation Effects on NERVA Structural Materials," pp. 625-52 in *Effects of Radiation on Structural Materials*, ASTM STP 426, American Society for Testing and Materials, Philadelphia, 1967.
37. P. Astruc, H. D. Harig, J. Sauvigne, and J. Verdier, *Source Froide du Reacteur a Haut Flux, Project de Realisation et Rapport de Surete*, Institut Max Von Laue - Paul Langevin, Grenoble, France, 1969.
38. R. P. Reed, "Aluminum. 2. A Review of Deformation Properties of High Purity Aluminum and Dilute Aluminum Alloys," *Cryogenics* 12, 259-91 (August 1972).

39. *Metals Handbook, Ninth Edition, Vol. 2, Properties and Selection: Nonferrous Alloys and Pure Metals*, American Society for Metals, Metals Park, Ohio, 1979.
40. R. P. Reed, R. P. Mikesell, and R. L. Greeson, "Some Mechanical Properties of Magnesium Alloys at Low Temperatures," p. 61 in *Symposium on Low-Temperature Properties of High-Strength Aircraft and Missile Materials, ASTM STP 287*, American Society for Testing and Materials, Philadelphia, 1961.
41. R. W. Fenn, Jr., "Low-Temperature Properties of Cast and Wrought Magnesium Alloys," p. 51 in *Symposium on Low-Temperature Properties of High-Strength Aircraft and Missile Materials, ASTM STP 287*, American Society for Testing and Materials, Philadelphia, 1961.
42. R. Nagasaki and K. Shiraishi, "Irradiation Effect on the Tensile Properties of Magnox Al80," *Journal of Nuclear Science and Technology* 2(10), 416-21 (October 1965).
43. J. Delaplace, J. Hillairet, J. C. Nicoud, D. Schumacher, and G. Vogl, "Low Temperature Neutron Radiation Damage and Recovery in Magnesium," *Physics Status Solidi* 30, 119 (1968).
44. S. Takamura and M. Kobiyama, "Recovery Stages in Mg, Zr, and Ti After Neutron Irradiation at Low Temperature," *Radiation Effects* 49, 247-50 (1980).
45. C. Pomar, T. H. Blewitt, and E. A. Bisogni, "Mechanical Properties of Low Temperature Irradiated Magnesium," *Physics Status Solidi (A)* 10, 519 (1972).
46. H. C. Gonzalez and C. J. Iriart, "The Mechanical Properties of Magnesium Irradiated by Fast Neutrons at 77 K," *Philosophical Magazine A* 52(2), 243-53 (1985).

Materials for Cold Neutron Sources: Cryogenic and Irradiation Effects

David Alexander

Questions/Answers/Comments

(E. Ottewitte)

Question:

Wouldn't the former Low Temperature Neutron Irradiation Facility at the Bulk Shielding Reactor (BSR) be the answer to supplying low-temperature neutron irradiation needs? Any hope of resurrection?

Answer:

Yes, to the first question; no, to the second.

(E. Ottewitte)

Question:

Should you not consider hydrogen embrittlement and hydrogen permeation in the selection of materials?

Answer:

This should not be a problem at low temperatures.

(P. Breant)

Question:

Could you explain, with more details, the importance of the ratio of thermal flux versus fast flux, and give, if possible, the acceptable limit?

Answer:

Thermal flux generates silicon; fast flux generates defects that allows the silicon to diffuse. However, at low temperatures, these diffusional processes are greatly reduced. The effect of the thermal to fast flux ratio will probably depend on the irradiation temperature. Further work is needed to define the limit or critical value.

(W. Sommer)

Question:

Where can you do irradiation testing at low temperatures on your candidate aluminum alloys?

Answer:

One possible site is the Bulk Shielding Reactor at Oak Ridge, although it appears unlikely that this facility will be restarted. I am not aware of any other facilities in the US.

(P. Ageron)

Question:

Is there a reduction of thermal conductivity of aluminum under irradiation at low temperatures?

Answer:

I do not know of any such measurements.

(T. Kawai)

Comment:

The wall thickness of the moderator cell is about 2 mm; the volume of the moderator cell is about 4L. The nuclear heating is about 70W when liquid hydrogen is used as a cold moderator.

Materials for Cold Neutron Sources: Cryogenic and Irradiation Effects

David Alexander

Questions/Answers/Comments

(N. Watanabe)

Question:

What do you think about the minimum acceptable life for the cryogenic moderator chamber for the Advanced Neutron Source? One month? One year?

Answer:

Without any mechanical property data for cryogenic irradiation conditions, any limit is completely arbitrary. I do not have any estimate for the life of the vessel.

(J. M. Carpenter)

Question:

What would be the lowest neutron fluences of interest in relation to low temperature materials tests?

Answer:

The available data indicate that a slight effect is already present at 10^{21} n/m². Therefore, this, or perhaps a slightly higher level (for example, 10^{22}), would be the lower limit.

(C. West)

Comment:

If workshop participants will send copies of reports, papers, or unpublished data on cold source materials (especially low-temperature irradiation properties) to the speaker, the ANS project will compile all the data and share them.

RADIATION EFFECTS CONCERNS AT A SPALLATION SOURCE

W. F. Sommer

Los Alamos National Laboratory
Los Alamos, New Mexico USA

ABSTRACT

Materials used at spallation neutron sources are exposed to energetic particle and photon radiation. Mechanical and physical properties of these materials are altered; *radiation damage* on the atomic scale leads to *radiation effects* on the macroscopic scale. Most notable among mechanical-property radiation effects in metals and metal alloys are changes in tensile strength and ductility, changes in rupture strength, dimensional stability and volumetric swelling, and dimensional changes due to stress-induced creep. Physical properties such as electrical resistivity also are altered.

The fission-reactor community has accumulated a good deal of data on material radiation effects. However, when the incident particle energy exceeds 50 MeV or so, a new form of radiation damage ensues; spallation reactions lead to more energetic atom recoils and the subsequent temporal and spatial distribution of point defects is much different from that due to a fission-reactor environment. In addition, spallation reactions cause atomic transmutations with these new atoms representing an impurity in the metal. The higher-energy case is of interest at spallation sources; limited detailed data exist for material performance in this environment.

At LAMPF we are developing aluminum-alloy vacuum chambers for use at the Proton Storage Ring. Radiation-effects studies have been done on aluminum alloy 6061. Also, development of 200 $\mu\text{g}/\text{cm}^2$ carbon stripper foils is underway. In collaboration with the Superconducting Super Collider design group, an irradiation-testing program aimed at developing radiation-hardened detector electronics is underway.

Previously, qualification of the properties of alloy Inconel 718 in a 760-MeV proton beam was completed; this material is used as the vacuum-to-air window at the LAMPF beam stop. At present, an irradiation test of the window design for SINQ, required to contain the liquid Pb-Bi target, is underway. The material under study here is a ferritic-martensitic stainless steel (Fe 12 Cr 1 Mo).

In this report, a survey of the basic mechanisms of radiation damage due to spallation reactions and the subsequent radiation effects is given. Research completed at LAMPF, and currently underway, is reviewed. At LAMPF, we utilize the Los Alamos Spallation Radiation Effects Facility at the beam stop as a large-volume neutron source for conducting experiments. Temperature control is easily achieved and mechanical and physical properties can be measured in-situ.

I. INTRODUCTION

When materials are exposed to energetic particle radiation, their mechanical and physical properties are altered. More than three decades of theoretical and experimental investigations on materials used in fission-based energy sources have produced solutions that allow operation for acceptable periods of time. For fission reactors, the damaging particles are neutrons with an average energy of about 0.5 MeV. The interaction of these neutrons with atoms in materials is largely an elastic scattering process. On average, 0.5-MeV neutrons transfer about 10 keV of energy to an atom in copper metal.^[1] This atom recoils and displaces additional atoms from their lattice sites. Energy is dissipated through displacements (binding energy per atom in Cu is about 30 eV) and through electronic losses. This radiation damage, in its most simple form, produces vacancies and interstitials that can cluster and produce the subsequent radiation effects.

At accelerator-based neutron sources, such as at the Los Alamos Neutron Scattering Center (LANSCE) at Los Alamos Meson Physics Facility (LAMPF), materials are exposed to higher-energy particles than in a fission reactor. Materials exposed to the primary 800-MeV proton beam (targets, beam-entry windows and beam-profile monitor elements) experience spallation reactions that result in recoiling atoms with energy up to several hundred keV.^[1,2] These spallation reactions produce a number of secondary particles including energetic protons and neutrons which, in turn, impinge on other components, primarily in target cells, and lead to further radiation damage.

The neutron spectrum produced by 800-MeV protons, such as at the LAMPF beam stop, resembles a fission spectrum at low energy but includes substantial numbers of neutrons with energy > 10 MeV.^[3,4] This spectrum is shown in figure 1 and is compared to the spectrum at a fission reactor and a spectrum such as is expected at a 14-MeV neutron source in a fusion energy device. It has been estimated^[1] that 26% of the atom-displacement damage in Cu produced by the LAMPF neutron spectrum is due to neutrons with energy > 20 MeV. The average energy transferred to a lattice atom in Cu by neutrons of energy > 100 MeV can reach 300 keV. The relationship between incident energy and average transferred energy is shown in figure 2.^[1,5]

Figure 1. Neutron flux per unit lethargy for LAMPF, EBR-II and RTNS-II, calculated for a proton beam current of 1 mA.

Figure 2. Average transferred energy versus incident neutron energy, 14 MeV neutrons^[5], and higher energy neutrons as calculated by VNMTC.

For 800-MeV proton radiation, as well as for exposure to a spallation neutron spectrum, higher transferred energies lead to larger zones of atomic disorder than for the fission-neutron case. In addition, spallation reactions produce sizable amounts of transmutation products that enter the metal as impurity atoms. The production of helium (α particle) in a spallation spectrum is similar in amount to that produced in materials at a fusion-energy device. The fusion-energy materials community has placed considerable attention on the effect of helium on material properties, since it is believed that helium is responsible for stabilizing vacancy clusters that become voids or gas bubbles in grain interiors and at grain boundaries. Macroscopic swelling and embrittlement are the subsequent consequences. Production rates of helium in metals by 800-MeV protons are more than 10 times greater than in the neutron cases above. For the proton case, measured cross sections^[6] are: Al (325 mb), Fe (500 mb), Ni (535 mb), Cu (510 mb), Mo (635 mb), W (760 mb) and Au (695 mb). Expressed as a concentration relative to the number of displaced atoms, the ratios range from 100-300 atomic parts per million per displacement per atom.

Considerable research on the effect of helium produced by medium-energy protons in pure metals has been conducted at RISO National Laboratory (RISO) in Denmark and the Paul

Scherrer Institute (PSI) in Switzerland. This work has used the Proton Irradiation Experiment (PIREX) facility at the PSI accelerator. The general observation is formation of an extensive void and bubble structure with attendant changes in mechanical properties.^[14,16]

A rather extensive compilation of data on radiation effects on materials used at accelerators, and hence at accelerator-based neutron sources, has been prepared by the European Organization for Nuclear Research (CERN).^[7] The vast majority of these data, however, were obtained by irradiation in a fission-reaction environment. At LAMPF, target design has proceeded in a systematic way and has produced reliable graphite production targets.^[8,9] Dedicated experiments at LAMPF^[10,11] have led to selection of alloy Inconel 718 as the LAMPF beam exit window and the selection of a ferritic-martensitic stainless steel (HT-9) as the candidate material for the Pb-Bi target interface at the Swiss Spallation Neutron Source (SINQ). Careful selection of material, design to low stress levels, selection of proven manufacturing processes and proper thermal heat control have led to reliable target cells at LAMPF.^[12]

At the LAMPF facility, with the exception of the studies noted above, most material performance upgrades have been realized after consideration of fission reactor experience and phenomenological observation. In most cases, more than one design iteration was necessary. A summary of the major observed difficulties at LAMPF and their solutions is given in Table 1. Figures 3 and 4 provide a "road map" for the areas at the facility referred to in Table 1.

A more systematic materials qualification approach was taken by the design group for the German Spallation Neutron Source (SNQ). Candidate materials were exposed to proper radiation environments at LAMPF, target materials were subjected to pulsed temperature as would be the case for the SNQ target, and new fabrication techniques were sought and developed.^[13] Unfortunately, this project was terminated in the design phase. Fortunately some relevant data were gathered.^[13]

TABLE I

LAMPF Subsystem	Radiation Source	Observed Damage Problems	Solution
Injector Region	Stripped electrons produce x-rays as they strike vacuum chamber walls and insulators.	High voltage breakdown due to microcracks in insulators, insulator surface modification. Charge exchange medium (Cs) contaminates surfaces.	Thermally stabilized ceramics, ceramic and glass coatings. Maintenance and cleaning program.
Accelerator, Area A, Area B and Area C.	Low level proton flux and concurrent neutron flux.	Failure of solid state components.	Localized shielding, placement of components in lower radiation fields, maintenance program.
Beam Switchyard (SWYD) Vacuum Chambers.	Low level off-momentum beam impinges on vacuum chambers, vacuum seals and vacuum chamber weldments.	Failed vacuum seals, cracked welds. Activation of components.	Localized shielding to facilitate hands-on maintenance. Larger apertures so that errant beam strikes specially designed beam stops rather than vacuum chamber walls. Improved weld design to eliminate thermal gradients.
SWYD, Area A, Area B and Area C Diagnostics.	Beam sensing elements are exposed to direct beam; low level and high level (100 μ A/ cm^2) 800 MeV protons.	Cracked and broken SiC and C wires (< 0.1 mm dia.)	Wires are spring loaded to maintain proper stress level. Wires are remotely driven through beam only during data acquisition time and then stored out of the beam.
All areas.	Charged particles and neutrons incident on water cooling systems.	Enhanced corrosion, failure of cooling lines, both polymers and copper metal.	Change to "rad hard" polymers wherever possible. Control water resistivity to > 1M Ω cm.
All areas.	Charged particles and neutrons incident on signal cables- 10^8 - $10^{10}/\text{cm}^2\text{s}$.	Brittle, failed insulation; short circuit to ground.	Change to Kapton insulation whenever possible.

Area A, A-1 and A-2 Targets	Primary beam of up to 8×10^{16} protons/cm ² s on graphite pion production targets.	Eroded and cracked graphite	Target is rotated so that proton pulses (120 Hz) do not strike same spot before one complete target rotation. Use pyrolytic graphite to enhance heat flux to heat sink along basal plane, reduces thermal gradients and stresses.
Area B and C, stripper foils.	Direct H ⁺ beam, ($< 3 \mu\text{A}/\text{cm}^2$)	Cracked and failed foils	Developed vapor deposited Al, Al ₂ O ₃ foils; resulting small grain size is more crack resistant.
Area A, Isotope Production Target Holders	Primary beam of $\sim 2 \times 10^{14}$ protons/cm ² s.	Bolted, metal sealed cover plate of aluminum alloy 6061 T-6 deformed causing massive cooling water leaks.	Material changed to 2000 series Al-Cu Alloy and welded construction. Less observed deformation.
Area A, Target Station A-6 Vacuum to Air Window	Primary beam of $\sim 2 \times 10^{14}$ protons/cm ² s	Stress induced cracking of alloy Inconel 718 flat plate windows causing massive cooling water leaks.	Design change to hemispherical, double walled window of alloy Inconel 718. Elimination of stress intensive areas, lower overall stresses
Area A, Target Cell Water Cooled Shielding	Spallation neutron, $10^{10} - 10^{12}$ neutrons/cm ² s and secondary proton flux.	Embrittled copper lines, stress corrosion cracking causing massive cooling water leaks.	Change to alloy 304 L stainless steel material, welded construction.
PSR Carbon Stripper Foils.	Primary proton beam ($5 \mu\text{A}/\text{cm}^2$) and circulating beam ($> 100 \mu\text{A}/\text{cm}^2$) in pulsed mode (up to 60 Hz)	Destruction of $200 \mu\text{g}/\text{cm}^2$ carbon foils, essential to the operation of the PSR.	Support foils with $4 \mu\text{m}$ C fibers to eliminate tearing stress and to support surface stresses.
PSR Vacuum Chambers	Proton and neutron flux, $10^8 - 10^{10}/\text{cm}^2\text{s}$.	Failed magnet vacuum chambers and water cooled high current conductors. Activated material, up to 50 Rem, hampering hands-on maintenance.	Larger apertures. Change to aluminum alloys which decay in radioactivity more rapidly.

Figure 3. Overview of LAMPF.

Figure 4. Schematic of the LAMPF experimental areas.

II. CONCERNS AT SPALLATION SOURCES

Materials used at fission reactors have been developed over the past three decades. Although some material-related difficulties still arise, fission reactor materials enjoy a rather sound theoretical framework, dedicated material test facilities, dedicated material test programs, dedicated manufacturing process development and a surveillance program. Material needs at spallation sources are small in volume relative to those at reactors. Here, dedicated test programs and commercial material development do not receive adequate attention. It becomes necessary to rely on fission-reactor experience; a problem arises because the details of radiation damage at the two radiation sources are different and the subsequent radiation effects do not necessarily correlate.

Radiation effects to materials generally manifest themselves as changes in physical and mechanical properties. Strength, ductility, rupture lifetime, and cyclic fatigue lifetime are all changed, generally in an adverse way. Volumetric swelling and stress-induced radiation-enhanced creep lead to dimensional changes that often cause difficulty. Radiation damage generally increases electrical resistivity and decreases thermal conductivity. High-strength alloys undergo phase changes due to radiation and charged-particle interactions with coolants can enhance corrosion.

Regardless of the radiation source, alloying enhances the ability of a material to successfully tolerate the environment. For example, the addition of Mg to Al serves to stabilize the dislocation structure produced by mechanical working (plastic deformation); the dislocations act as annihilation sites for radiation-produced point defects. Small grain size, induced by several alloying techniques, provides a larger grain-boundary area for absorption of radiation-produced point defects and impurities; a large concentration of vacancies or impurities at grain boundaries can cause intergranular cracking and grain-boundary failure. Classically, the addition of Cr in Fe forms a corrosion barrier of Cr_2O_3 on the material surface. Alloys have been specifically developed for use in fission reactors; no significant development has taken place for spallation-source environments.

Since the material needs at spallation sources are small in volume and schedules demand finished components in a short time, dedicated material-development studies are not gener-

ally pursued. As designs become more complex and costly, this option should be seriously considered; the opportunity for this development exists at the Los Alamos Spallation Radiation Effects Facility (LASREF). Over the past several years, LASREF has been utilized to address critical material problems at LAMPF and elsewhere; some of these are described below. Details of the LASREF are also given below.

III. RADIATION-EFFECTS EXPERIMENTS AT HIGH-POWER ACCELERATORS

Test Facilities

Almost all experimental effort in the area of high energy (>10 MeV) neutron and proton radiation-effects studies has taken place at PIREX at PSI in Switzerland and at LASREF at LAMPF. Early work at PIREX centered around determination of microstructural evolution and microstructural stability in aluminum; the damaging particles were 600-MeV protons.^[14-17] Work at PIREX and LASREF^[1-4,6] has determined radiation damage parameters for these sources for 600-800 MeV protons and spallation neutrons. The details of the PIREX Facility are given in Reference 17; a brief description of LASREF follows in this text.

At Los Alamos, a theoretical framework for predicting microstructural evolution caused by high-energy cascades was initiated.^[18,19] This theoretical work is continuing at PSI and at the Institute for Atomic Energy in the Peoples Republic of China. At LAMPF, an experiment in which pure materials were exposed to 800-MeV protons and high-energy neutrons to similar doses is aimed at determining differences in microstructural evolution and at comparison of these results to theoretical predictions. In addition, identical material has been exposed to the fission-neutron flux at the Danish DR-3 reactor at RISO. Most of the transmission electron microscopy investigation of the microstructure is being completed at RISO. The goal of this entire exercise is twofold; to compare the different sources by observation of a basic radiation effect and to compare them all to an advanced theoretical model.

Magnetic Materials

Experiments at LAMPF on high permeability materials^[20,21] have shown that a metallic glass, METGLAS 2605S-3, suffers less degradation in permeability than does mu metal. This material is used as a transformer in toroidal geometry as a current monitor throughout LAMPF. Although mu metal has superior permeability in the unirradiated state, it rapidly degrades, requiring costly replacement of current monitors in high-radiation areas at least once a year. The metallic glass suffers very little degradation and should extend the lifetime of the current monitors. Figure 5 compares the influence of neutron radiation in the two materials.

Figure 5. The effect of neutron fluence on the permeability of 2605S-3 a metallic glass, and Mu Metal. Reprinted with permission from the author.^[20,21]

Proton-Beam Exit Windows

Dedicated experiments^[11] have qualified alloy Inconel 718 as the beam-exit vacuum-to-air window at the LAMPF beam stop. One such window, on the beam stop itself, has endured a fluence of approximately 10^{26} protons per m^2 over the last five years.

The Paul Scherrer Institute (PSI) is in a final design effort aimed at achieving a high neutron flux for neutron scattering experiments, at the SINQ facility. Their concept uses a liquid Pb-Bi target that produces neutrons through spallation reactions with incident 600-MeV protons; neutrons are moderated to proper energies for neutron-scattering experiments. They require a window to separate the Pb-Bi from the accelerator and

transport-line vacuum chamber. Nickel-based alloys are generally not acceptable for use in contact with Bi because of a strong chemical corrosion effect. Brown, et al.,^[10] performed controlled tests on Fe-2.25 Cr-1 Mo and Fe-12 Cr-1 Mo (HT-9) alloys, where the radiation conditions are essentially identical to those expected at SINQ. After achieving a dose of 5×10^{24} protons/m² on specially prepared tensile samples, they concluded that either alloy was suitable; little change in strength or loss of ductility was observed nor was any corrosion of the material in contact with Pb-Bi observed. Figure 6 shows the stress-strain behavior of alloy HT-9; note in contrast the drastic effect of spallation neutrons on the mechanical behavior of pure tantalum. At present, as a further test of this material (HT-9) and window concept, full-scale windows under stress are being irradiated at LAS-REF to end-of-life-expectancy doses; these tests are necessary for licensing procedures in Switzerland.

Figure 6. The influence of spallation neutrons on the mechanical properties of alloy HT-9 and pure tantalum. High fluence was $5.4 \times 10^{24}/\text{m}^2$; low fluence was $4.8 \times 10^{23}/\text{m}^2$. Reprinted with permission from the author.^[10]

Semiconductor Devices

Instrumentation in nuclear and particle physics is at a new juncture with new accelerators, such as the Superconducting Super Collider (SSC), capable of delivering large particle fluxes, which strain the performance of semiconductor detectors based on conventional technology. On the other hand, commercial development in the semiconductor industry is so rapid that custom-designed detector readout systems are now feasible. The challenge is to develop readout systems that can handle large data rates and survive the associated large radiation doses.

At SSC, it is estimated that there will be about 10^8 collisions per second,^[22] each producing an average of over 100 charged particles, which results in large charged-particle fluxes passing through the detectors and the read-out electronics mounted on the detectors. Charged-particle dose rates are expected to be about 1 Megarad/year (114 R/hr). In addition, the expected neutron flux is estimated at $10^{19}/\text{m}^2$ year. Because the neutrons result from a hadronic cascade, the typical neutron energy is 1 MeV, but there is a non-negligible high-energy tail.

Because the physical effects of high-energy ions and neutrons are quite different, testing with both types of particles has proceeded in parallel. Proton fluxes in the range 2×10^{10} to $2 \times 10^{12}/\text{m}^2\text{s}$, as available in Area C, have been used. LASREF offers a large volume at neutron fluxes in the $10^{12} - 10^{14}/\text{m}^2\text{s}$ range, at energies appropriate to the SSC, and has been used for several tests. Results from the initial neutron irradiations at LASREF show promise for developing radiation-hardened transistor and readout chip assemblies.^[23] Several additional irradiations were conducted during 1989 and are now being analyzed.

Carbon Stripper Foils

The Proton Storage Ring (PSR) at LAMPF receives an 800-MeV H^- beam from the accelerator. The H^- is stripped to H^0 (one proton and one electron, net charge of zero) by a strong magnetic field, to facilitate non-reactive injection into the ring through a bending magnet. To allow transport around the ring, the particles must again have a charge. The beam is stripped of its remaining electron to H^+ ; this requires that the H^0 beam pass through a $200 \mu\text{g}/\text{cm}^2$ carbon foil. Foils used during the initial operation of PSR failed by tearing and curling after a few hours of bombardment by the beam of about 10^{20} 800-MeV $\text{H}^0/\text{m}^2/\text{s}$. In collaboration with scientists at Pacific Northwest Laboratory and Westinghouse Hanford Company, a new design was perfected that suspends a 1.6-cm square foil on a grid of $4 \mu\text{m}$ diameter carbon fibers. Tearing stresses are thus eliminated and surface stresses are supported by the fibers. Lifetime of the foils has been extended to two to three weeks with considerable savings in time and radiation exposure to staff; the stripper mechanism and vacuum chamber become activated and decay at levels of several rem/h.

Aluminum Alloys

Lohmann, et al.,^[13,24] studied the mechanical property changes under proton radiation in aluminum alloy 6061 and cold-worked Al Mg3 alloy for application to the structural and cladding components of the German SNQ neutron production target, proposed to be made of a uranium alloy. A drastic decrease (250-50 MPa at room temperature) in yield strength was observed for both alloys after a fluence of 3.2×10^{24} protons/m². Transmission electron microscopy showed that the Mg₂Si precipitates in alloy 6061-T6 had dissolved and the cold-worked dislocation structure in the Al Mg3 alloy had annealed. Irradiation temperature was only 40–50°C. These findings are in sharp contrast to those obtained in similar material exposed to a fission neutron spectrum.^[25] As seen in figure 7, the fission-neutron data show a gradual increase in yield stress with fluence while the 760-MeV proton data shows a drastic decrease. Since there is continuing interest at LAMPF and at spallation neutron sources in the use of this alloy, additional irradiations to several fluences were completed; examination of these samples is now underway.

Figure 7. Effect of fission neutron irradiation on the yield strength of aluminum alloy 6061 T-6 compared to the effect by 760 MeV protons.

Aluminum alloy 6061-T6 is a candidate material for vacuum chambers in the Proton Storage Ring (PSR), where proton beam losses activate materials to levels of several rem/h and complicate hands-on maintenance procedures. The present material used is 304L stainless

steel. The advantage of using the aluminum alloy can be seen in figure 8. Two plates, identical in dimension, one of 304L stainless steel and another of 6061 aluminum, were simultaneously irradiated in the same location by stray protons and spallation neutrons in the PSR.^[26] Dose-rate measurements as a function of time after irradiation clearly show that the radiation exposure to workers is substantially less for the aluminum alloy after a one-day cool-down period and beyond. Alloy 6061 is preferred for application to vacuum chambers because of superior welding characteristics; allowance for the decrease in yield strength, as noted above, is made in the design.

Figure 8. Dose rate as a function of decay time for aluminum alloy 6061 and stainless steel alloy 304L.

Radiation levels in the PSR during operation are high enough that elastomer vacuum seals are generally not acceptable. At LAMPF, 1100-0 aluminum wire rings are used in these seals and have been shown to be acceptable for vacuum applications at the 10^{-8} Torr level. When consideration was given to the use of aluminum-alloy vacuum chambers, there was a concern that after deformation of the 1100-0 wire of about 50%, its hardness would become comparable to the 6061 T-6 alloy and, in turn, deform the sealing surface of a vacuum chamber. Tests confirmed this possibility; the potential for destroying an expensive and complicated vacuum chamber existed. In an attempt to harden vacuum-sealing surfaces of

6061 alloy chambers, test samples were bombarded with 100-200 keV nitrogen ions at the Los Alamos Ion Beam Facility. Rutherford back-scattering studies, using 3-MeV alpha particles, show an AlN structure to a depth of 0.5 μm ; nano hardness measurements show a maximum increase in hardness in this layer of about 4 times. This method of surface hardening has the advantage of providing a gradient in hardness that is less likely to form microcracks. These microcracks lead to small vacuum leaks and are present when the more conventional anodizing procedures are used; here a very hard Al_2O_3 layer forms a sharp interface with the softer base material. Our results thus far encourage us to continue this development by applying the technique to full-scale chambers.

Basic Experiments

A number of experiments, devoted to understanding basic radiation effects phenomena due to high-energy particles have been completed at LAMPF and elsewhere. Field Ion Microscopy (FIM) studies have observed atomic resolution detail of depleted zones in W metal that involve several hundred lattice sites.^[27-29] Microstructural evolution due to 800-MeV proton bombardment has been observed and documented.^[14-17,30,31] Utilizing the large volume available at LAMPF, an *in-situ* study used 800-MeV protons as a radiation source and found that dislocations set into motion by an applied cyclic stress were effective in reducing void formation in cyclically stressed aluminum by "sweeping up" excess radiation-produced vacancies.^[32]

IV. LASREF FACILITY DESCRIPTION

The Los Alamos Spallation Radiation Effects Facility (LASREF) is located at the beam-stop area (Target Station A-6) at LAMPF. The design of this facility is modular in that each component and experiment is attached to its own biological shield plug (insert). This can be seen by noting a schematic (figure 9) and a photograph (figure 10). The biological shield is necessary for containment of the radiation produced along the beamline, at the isotope production bulk targets, and at the beam stop. Services, such as cooling water and instrumentation cabling, are routed through stepped slots in the biological shield to the top of the facility. Instrumentation cabling is further routed through a maze in a

Figure 9. Schematic of LASREF.

Figure 10. A proton irradiation insert and capsule in preparation for installation.

secondary containment concrete hut to an area that is accessible when beam is on, where instrumentation cabinets can be located. This can be seen in schematic form in figure 9.

Three independent insert locations (proton irradiation inserts) are available for placing capsules in the direct proton beam. Their relationship to other components at Target Station A-6 is shown in a side view in figure 11. The irradiation volume for each is about 150 cm^3 . It is possible to modify the insert to accommodate more sensitive equipment in a position removed from the beamline where both shielding and distance decrease the particle radiation flux.

Figure 11. Side view of LASREF.

Twelve independent insert locations (neutron irradiation inserts) are available for placing capsules in the neutron flux. Figure 12 shows their relationship to other components at Target Station A-6 in a top view and figure 13 shows, schematically, their relationship to the neutron-producing targets. Protons, in comparable number, are also produced by spallation reactions in the targets but $\sim 90\%$ are absorbed in the target material.^[1,2] This is also the case for most other secondary charged particles produced in the targets. Each insert location has a 12- by 25- by 50-cm volume available for irradiation capsules whose geometry and complexity is left to the discretion of the experimenter.

NEUTRON AND PROTON PORTS ARE RECEPTACLES FOR THE INSERTS.

Figure 12. Top view of LASREF showing the spatial relationship of the inserts.

Figure 13. Schematic of the neutron irradiation inserts showing their spatial relationship to the neutron-producing targets at LASREF.

Although LAMPF accelerates protons to a maximum energy of 800 MeV, interactions with two graphite targets upstream from the facility lower the energy to about 760 MeV. At a nominal total beam current of 1 mA and a Gaussian-like beam spot size of diameter 5 cm to 2σ (σ is one standard deviation), it has been calculated^[1] that a displacement rate of 8.4×10^{-7} displacements per atom per second (dpa/s) is obtained in copper metal at

the center of the beam. The average beam current delivered to LASREF is typically 0.8 mA with an availability of 80%, about 0.3 dpa can be expected per week in copper metal. LAMPF operates about 6 months per year.

Calculations and measurements^[3,4] have been made of the particle flux and spectrum (figure 1) incident on the neutron-irradiation volumes. At position 2 in figure 12, the total neutron flux is about 5.5×10^{17} n/m²s at 1 mA of proton beam current, giving a displacement rate of 4×10^{-8} dpa/s in copper metal.^[1] For the conditions normally available (0.8 mA and 80% availability), a total atom displacement of 0.14 dpa would be achieved in nine-weeks in copper metal. The flux drops along the beamline from position 2 to a minimum at positions 8 and 12, $\sim 10\times$ lower than at position 2. Calculations and measurements^[4] have also shown that the secondary charged-particle flux at the inner surface (nearest the beamline) of the neutron-irradiation volumes is about 10% of the neutron flux. An additional 1 cm of iron shielding further reduces the charged-particle flux to about 1% of the neutron flux.

A more detailed description of the facility has been prepared.^[33,34] A summary report of the facility, past and current experiment objectives and guidelines for conducting research at LAMPF is also available.^[35]

V. CONCLUSIONS

1. Fission-reactor experience with material radiation effects does not necessarily correlate with that at spallation sources.
2. Dedicated studies at LAMPF have produced reliable data on proton-beam exit windows.
3. LASREF offers an opportunity to conduct basic and applied research on radiation damage and radiation effects under high-energy particle bombardment.

VI. REFERENCES

1. M. S. Wechsler, D. Davidson, L. Greenwood, and W. Sommer, "Calculation of Displacement and Helium Production at the LAMPF Irradiation Facility," ASTM STP 870 (1985), 1189.

2. C. Coulter, D. Parkin, and W. Green, "Calculation of Radiation Damage Effects of 800 MeV Protons in a 'Thin' Copper Target," J. Nucl. Mater., **67** 140-154 (1977).
3. D. Davidson, L. Greenwood, R. Reedy, and W. Sommer, "Measured Radiation Environment at the LAMPF Irradiation Facility," ASTM STP 870 (1985), 1199.
4. D. Davidson, R. Reedy, L. Greenwood, W. Sommer, and M. Wechsler, "Additional Measurements of the Radiation Environment at LASREF," ASTM STP 956 (1987), 730.
5. C. Logan and E. Russell, "Radiation Damage at the Rotating Target Neutron Source (RTNS-I) Facility at Lawrence Livermore Laboratory," UCRL-52093, Lawrence Livermore Laboratory, Livermore, CA, 1976.
6. S. Green, W. Green, F. Hegedus, M. Victoria, W. Sommer, and B. Oliver, "Production of Helium by Medium Energy (600-800 MeV) Protons," J. Nucl. Mater., 155-157 (1988), 1350.
7. P. Beynel, P. Maier, and H. Schenbacher, "Compilation of Radiation Damage Test Data Part III, Materials Used Around High Energy Accelerators," European Organization for Nuclear Research, CERN 82-10, 4 November 1982.
8. R. D. Brown and D. L. Grisham, "Design and Operation: Water-Cooled Pyrolytic Graphite Targets at LAMPF," IEEE Transactions in Nuclear Science, **NS-28**, 2940 (1981).
9. R. D. Brown and D. L. Grisham, "Graphite Targets at LAMPF," IEEE Transactions on Nuclear Science, **NS-30**, 2801 (1983).
10. R. D. Brown, M. S. Wechsler, and C. Tschalär, "Tensile Properties of Several 800 MeV Proton-Irradiated bcc Metals and Alloys," ASTM STP 956 (1987), 131.
11. R. Brown and J. Cost, "Mechanical Properties of 800 MeV Proton Irradiated Metals," ASTM STP 782 (1982), 917.
12. L. Agnew, D. Grisham, R. J. Macek, W. F. Sommer, and R. D. Werbeck, "Design Features and Performance of the LAMPF High Intensity Beam Area," ICANS VII, Chalk River, Ontario, Canada, Sept. 12-16, 1983. Published in the Proceedings.
13. W. Lohmann and W. F. Sommer, "Materials Problems Relevant to a Pulsed High Power Spallation Target," Rutherford Appleton Laboratory Report, ISIS/PGT/15 (1986).
14. M. Victoria, W. Green, B. Singh, and T. Leffers, "Nucleation, Growth, and Distribution of Cavities in the Vicinity of Grain Boundaries in Aluminum Irradiated with 600-MeV Protons," ASTM STP 955, 233.
15. D. Gavillet, W. Green, M. Victoria, R. Gotthardt, and J. Martin, "In-Situ Electron Microscopy Observation of Dislocation Motion in 600-MeV Proton Irradiated Aluminum," ASTM STP 955, 490.

16. F. Paschoud, R. Gotthardt, and S. Green, "Stability Studies of Radiation Defects in Aluminum Introduced by 600-MeV Protons," ASTM STP 955, 478.
17. D. Gavillet, R. Gotthardt, J. Martin, S. Green, W. Green, and M. Victoria, "Helium and Displacement Damage Produced by 600 MeV Proton Beams in High Purity Aluminum," ASTM STP 870, 394.
18. J. Yu, W. Sommer, and J. Bradbury, "Nonequilibrium Statistical Theory of Bubble Nucleation and Growth under Neutron and Proton Irradiation," J. Nucl. Mater. 141-143 (1986), 658.
19. J. Yu, "Interstitial Dislocation Loop Nucleation and Growth and Swelling Produced by High Energy Cascades," ASTM STP 955 (1987), 393.
20. R. D. Brown, J. R. Cost, and J. T. Stanley, "Effects of Neutron Irradiation on Magnetic Permeability of Amorphous and Crystalline Magnetic Alloys," J. Appl. Phys. 55, 1754 (1984).
21. R. D. Brown, J. R. Cost, and J. T. Stanley, "Irradiation-Induced Decay of Magnetic Permeability of Metglas 2605S-3 and Mu Metal," J. Nucl. Mater., 131, 37 (1985).
22. "Radiation Levels in the SSC Interaction Regions," edited by D. E. Groom, SSC Central Design Group, Task Force Report, SSC-SR-1033, June 10, 1988.
23. H. Sadroziński, W. Rose, A. Seiden, E. Spencer, C. Hoffman, D. Holtkamp, W. Kinnison, W. Sommer, and H. Ziöck, "Test of Radiation Hardness of CMOS Transistors under Neutron Irradiation," Proceedings of the Fifth Symposium on Semiconductor Detectors, Munich, West Germany, February 21-23, 1989.
24. W. Lohmann, A. Ribbens, W. Sommer, and B. Singh, "Microstructure and Mechanical Properties of Medium Energy (600-800 MeV) Proton Irradiated Commercial Aluminum Alloys," Rad. Effects 101 (1987).
25. K. Farrell and R. King, "Tensile Properties of Neutron Irradiated 6061 Aluminum Alloy in Annealed and Precipitation Hardened Conditions," ASTM STP 683 (1979), 440.
26. P. D. Ferguson, "Dose Rate Curves for Aluminum Alloy 6061 and Stainless Steel Alloy 304," Internal Memorandum, Group MP-5, Los Alamos National Laboratory, Los Alamos, New Mexico, August 31, 1989.
27. D. J. Farnum, W. F. Sommer, and O. T. Inal, "A Study of Defects Produced in Tungsten by 800-MeV Protons Using Field Ion Microscopy," J. Nucl. Mater. 122,123 996-1001 (1984).
28. D. Farnum, W. Sommer, O. Inal, and J. Yu, "Quantitative Study by Field Ion Microscopy of Radiation Damage in Tungsten after Proton and Neutron Irradiation," ASTM STP 955 (1987) 90.
29. O. T. Inal and W. F. Sommer, "800-MeV Proton Damage in Tungsten and Molybdenum A Field-Ion Microscope Observation," J. Nucl. Mater. 99, 94-99 (1981).

30. H. Jang, J. Moteff, L. Levinson, R. D. Brown, and W. F. Green, "Defect Formation in 800-MeV Proton Irradiated Aluminum," Los Alamos National Laboratory Report, LA-8127-MS (1979).
31. R. D. Brown, W. F. Sommer, and W. V. Green, "Irradiation Damage in Metals Produced by 800-MeV Protons," Los Alamos National Laboratory Report, LA-7939-MS (1979).
32. W. F. Sommer, D. S. Phillips, W. V. Green, L. W. Hobbs, and C. A. Wert, "Proton Irradiation Damage in Cyclically-Stressed Aluminum," J. Nucl. Mater. **114**, 267-276 (1983).
33. M. S. Wechsler and W. F. Sommer, "The Radiation Damage Facility at the LAMPF A-6 Target Station," J. Nucl. Mater. **122,123**, 1078-1084 (1984).
34. W. Sommer, W. Lohmann, K. Graf, I. Taylor, and R. Chavez, "Operating Experience at the Los Alamos Spallation Radiation Effects Facility at LAMPF," ASTM STP 956 (1987), 718.
35. W. F. Sommer, "Summary of the Los Alamos Spallation Radiation Effects Facility (LASREF) at LAMPF," Proceedings of the 10th Meeting of the International Collaboration on Advanced Neutron Sources held at Los Alamos, 3-7 October 1988, Institute of Physics Conference Series Number 97, Institute of Physics, Bristol and New York, 865.

Radiation Effects Concerns at a Spallation Source

Walter F. Sommer

Questions/Answers/Comments

(W. Bernnat)

Question:

Which neutron cross sections did you use in the Monte Carlo calculations for the energy range from 15 meV to 200 meV? Also, did you employ the intranuclear cascade model implemented in HETC or a pre-equilibrium model?

Answer:

The calculations, completed in 1983, used the ENDF/B-V cross-section data files. Estimates for ^{85}Rb , ^{87}Rb , ^{133}Cs , ^{79}Br , and ^{127}I were provided by the Los Alamos Nuclear Data Group. For HETC, the intranuclear-cascade-evaporation model, implicit in this code, was used.

(J. Verdier)

Comment:

In the case of materials to be used for cold neutron sources cells, there are three separate causes of damage.

- Thermal neutrons cause build up of undesirable elements.
- Fast neutrons cause radiation damage in the metal structure.
- H_2 on D_2 can diffuse inside the metal and cause embrittlement.

One has to consider the synergistic effects of all parameters. This means that any material irradiation program should consider full-size experiments able to simulate these synergistic effects, for example, silicon buildup in the ILL cold source and He buildup and H_2 diffusion in the ORPHEE cold sources.

I n s t r u m e n t a t i o n & C o n t r o l s a t R e a c t o r C o l d N e u t r o n S o u r c e (I n c l u d i n g L i n k s t o R e a c t o r C o n t r o l s)

Takeshi Kawai and Yutaka Maeda

Research Reactor Institute, Kyoto University,
Kumatori-cho, Sennan-gun, Osaka, 590-04, Japan.

ABSTRACT

This report describes how to measure and how to control the liquid level in the cold moderator cell. We report also links to reactor controls for reactor safety.

1. INTRODUCTION

Principal design criterion of a cold neutron source(CNS) is to maximize a cold neutron flux and supply a stable cold neutron flux over a long time. Although solid methane is far better as a cold moderator, liquid hydrogen and liquid deuterium are used in many reactor cold neutron sources because they have suitable characteristics in cross sections, controlling easiness,

removability of nuclear heating and the less radiation damage in contrast to solid moderators. In order to supply a stable cold neutron flux using liquid cold moderator, it is necessary to control liquid level in the moderator cell stable over a long time. Furthermore, controls to keep the moderator from sudden bubbling and boiling is required.

Another design criterion of the cold neutron source is the safe operation towards personnel and the reactor. We report the instrumentation and links to reactor controls which satisfy the requirements for a system to be efficient and safe.

II. COLD NEUTRON SOURCE FACILITY

Structural design of CNS depends mainly on differences in cooling system of cold moderator. Cooling systems of hydrogen are divided into the following two classes: (i) one is a direct cooling system in which hydrogen is liquefied by expanding adiabatically after being compressed, (ii) another is an indirect cooling system in which hydrogen is liquefied by contact with refrigerant, that is, liquid hydrogen or cold helium gas. A significant disadvantage of the former is that inflammable gas is compressed in high pressure though the efficiency of heat exchange is high. Air is easily leaked in the hydrogen system due to insufficient air-tight of the compressor. The cold helium gas is usually used as a refrigerant than a liquid hydrogen in the latter cooling system from the point of view of the safe operation. The latter is further classified into three different types according to the place for a heat exchanger to occupy.

HFBR CNS in BNL belongs to the first type, in which the moderator cell itself acts as the heat exchanger and gaseous hydrogen transported from a gas cylinder is liquefied in the moderator cell by heat exchange with a cold helium gas. The important points on applying this system to CNS could be as follows: (i) when a wall is thick or nuclear heating of the wall

is large, not only removing of nuclear heating but also storing liquid in the moderator cell is not attained, because the temperature in the wall of the moderator cell becomes higher than the boiling point of hydrogen, (ii) even if the suitable temperature difference is obtained across the wall, the cooling pipes should be wound closely to keep the intermediate temperature between them lower than the boiling point of hydrogen. This causes an extra nuclear heating and the absorption of cold neutrons. Furthermore, it is difficult to keep the liquid hydrogen from solidifying. This type of the cooling system is thus inappropriate to the reactor cold neutron source.

HFR-CNS at ILL with a closed-thermosiphon is of the second type in which gaseous deuterium from the buffer tank is liquefied by heat exchange with cold helium gas in a condenser located in a separated region from the moderator cell, and liquid deuterium is transported to the moderator cell by the gravitational force via vertical moderator transfer tube against the upward flow of the deuterium vapor. ORPHEE-CNS belongs also to this type. The third type is FRJ-2 CNS in Julich in which gaseous hydrogen is liquefied partially in the heat exchanger and transported to the moderator cell being further cooled by contact with cooler. The characteristics of typical cold neutron sources are summarized in table 1.

When the moderator transfer tube is so designed and constructed as to fulfill certain conditions, the closed-thermosiphon cooling system is one of the best selections for the reactor cold neutron source^{(1),(2),(3)}. We thus describe the instrumentation and controls of the closed thermosiphon type CNS in the next section.

III. INSTRUMENTATION & CONTROLS OF THE CLOSED THERMOSIPHON TYPE CNS

We shall now try to discuss regarding some countermeasures to

Table 1. Typical examples of a cold neutron source with
a different type of a cooling system.

	HFBR (BNL)	FRJ-2 (Jülich)	FGHFR(ILL)	ORPHEE(Saclay)	KUR (Japan)
Reactor power	60 MW	15 MW	57 MW	11 MW	5 MW
Moderator	Heavy water	Heavy water	Heavy water	Heavy water	Water
n_{th}	$1 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$	$8 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$	$1.5 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$	$3 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$	$1 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$
Mod. cell	A-6061-T4	Al-Mg alloy	Al-alloy	Stainless steel	A-5052
Vac. chamber	A-6061-O		Zircaloy		A-5052
Cold moder.	20K liq. H ₂	20K liq. H ₂	25K liq. D ₂	20K liq. H ₂	28K liq. D ₂
Initial press.	~5 atm		3 bar	~4 atm	4.7 atm
Mod. volume	~1.6 litres	3.5 litres	25 litres	~0.7 litres	~4 litres
Tank volume	—	~2 m ³	18 m ³	~0.5 m ³	2.7 m ³
Nucl. heating	~700 W	~500 W	~7 kW	~700 W	~100 W
Cooling loop	Heat exchange at mod. cell	Combination of two method (Horiz.)	Closed-thermosiphon (Vertical type)	Closed-thermosiphon (Vertical type)	Closed-thermosiphon (Horizontal type)
Pumping system	Turbomole. pump	Turbomole. pump	Diffusion pump	Cryo pump	Turbomole. pump
Preventing system of air leakage	Helium barrier system	Helium barrier system	In water pool	In water pool	Helium barrier system
Prevention of H ₂ solidifying	Refrigerant temp. at inlet of condenser > 14K	Refrigerant temp. at inlet of condenser > 14K			Refrigerant temp. at inlet of cond. > 18.6K
Cooling system for vac. chamber	Cooling loop of water	Cooling loop of heavy water			Purging He gas in a vac. chamber
Protection of vac. chamber	Safety relief valve	Rupture disc	Rupture disc		Rupture disc
Instrumentation	<ul style="list-style-type: none"> • Uninterruptible power supply • Residual gas analyser • Monitor of vac. 		<ul style="list-style-type: none"> • Residual gas analyser • Monitor of vac. 	<ul style="list-style-type: none"> • Residual gas analyser • Monitor of vac. 	<ul style="list-style-type: none"> • Uninterruptible power supply • Residual gas analyser • Gas chromatography • Monitor of vac.
Parameters linked to reactor shut down	Loss of coolant to the vac. chamber & moderator cell	<ul style="list-style-type: none"> • Overheating of vac. chamber • Overheating of mod. cell • Refrigerator failure 		<ul style="list-style-type: none"> • Overpressure in vac. chamber • Overpressure in H₂ tank • Refrigerator failure 	<ul style="list-style-type: none"> • Overpressure in vac. chamber • Overpressure in H₂ tank • Uninterrupt. power supply failure

the aspects of keeping liquid level in the moderator cell under control. The closed-thermosiphon system generally consists of a hydrogen system and a helium cryogenic loop as shown in fig. 1. The main part of the helium cryogenic loop is a combination of the helium compressor and the helium refrigerator. The closed hydrogen system consists of a hydrogen cold system and a hydrogen reservoir tank. The hydrogen cold system includes a moderator cell, a moderator transfer tube and a condenser. The idealized thermosiphon cooling system without a flow resistance in the moderator transfer tube shows an excellent characteristics, that is, a characteristic of self-regulation to the heat load fluctuations and the liquid level in the moderator cell is kept almost constant within the certain range of the heat load due to this property⁽⁴⁾.

The mechanism of self-regulation is as follows: when the thermal load is applied to the idealized hydrogen cold system, the pressure in the system rises by the evaporation of liquid hydrogen and the boiling point of hydrogen rises. Since the helium temperature at the outlet of the condenser rises in contrast to the stable inlet temperature, the liquefaction capacity of the condenser apparently increases because the refrigerating power of the helium refrigerator increases with a rise of temperature. Therefore, the effect of evaporation of liquid due to the thermal load increase is compensated and canceled though the system is in a state of a slightly higher temperature.

Such a closed-thermosiphon is said to have self regulation to the thermal load fluctuations and the CNS with a self-regulating characteristics keeps the liquid level stable in the moderator cell. The stable supply of cold neutron flux, thus, results in.

The closed thermosiphon has also the following peculiarities with respect to the safe operation and controls: (i) it is easy to keep air from leaking into the hydrogen system and check the leakage of hydrogen. (ii) it is easy to keep the liquid hydrogen

Fig. 1. Instrumentation of a cold neutron source with a closed-thermosiphon.

from solidifying and sudden bubbling by controlling the operational pressure of CNS higher than the atmospheric pressure.

Boiling point of hydrogen is determined by the pressure of the closed system and these quantities are related to each other through the vapor pressure curve. Therefore, moderator temperature and level in the moderator cell may be known only by measuring the pressure of the reservoir tank if the phenomena with a time lag is not generated in the moderator transfer tube. Since the fluctuating range of the power in the reactor operated stationarily is less than 5 %, the liquid level in the moderator cell is kept almost constant in the CNS with the self-regulation within the range of about 30 % of the maximum heat absorption capacity to the heat load fluctuations. A fully automated operation is possible by controlling the pressure of the reservoir tank using the PID processor in such a CNS. The machinery controls the power of heater in the refrigerant helium at the outlet of the refrigerator so as to make the difference between the process value and its preset value zero. This preset value is the manipulated value determined by the deviation of the pressure of a reservoir tank from the preset value of the operating pressure of the CNS.

The gas chromatography and the mass analyzer are required most to the safety controls of CNS. Gas chromatographies are equipped to the refrigerant helium system and the hydrogen system for checking the leakage of air or the penetration of hydrogen into helium. The residual gas in a vacuum chamber is monitored by the mass analyzer. The steady operating pressure of the refrigerant helium system is higher than that of the hydrogen system to prevent the hydrogen from penetrating into a refrigerant. Therefore, the T-S diagram of the refrigeration is a 2-stage reversed brayton cycle.

The vacuum gauges equipped in the vacuum chamber form the 2 out of 3 system as well as the pressure gauges in the reservoir tank.

In order to prevent the CNS facility interfering with the continuous operation of a reactor, the cooling system of the moderator cell is required when we found it difficult to operate the refrigerator. This cooling system is determined by the magnitude of nuclear heating.

Helium charging loops are necessary to pour helium gas into the vacuum chamber and the venting line for the purpose of preventing the explosion of ozone and hydrogen in case of leakage.

The refrigerant is by-passed to keep the moderator from solidifying when the helium temperature at the inlet of the condenser becomes the lower limit.

IV. LINKS TO REACTOR CONTROLS

The important safety aspects of the reactor cold neutron source are as follows: (i) reactor safety, (ii) personnel safety and (iii) the protection of the CNS facility. Beyond the design and the construction focused on the facility protection, the safe operating procedures with regard to the hydrogen hazard is required to be built in the design and operational control for the personnel and reactor safety.

Since the vacuum chamber is the main protective barrier between the reactor vessel and the hydrogen, it ought to be designed to contain the maximum credible pressure from the hydrogen-oxygen reaction. Mixing hydrogen and oxygen is prevented by monitoring the pressure of the hydrogen and checking the air contamination of hydrogen with the gas chromatographies before start up. Hydrogen is automatically vented with a bulk quantity of helium gas from the emergency He gas supply system through the stack if the pressure of the reservoir tank passes preset limits. This causes the reactor to be shut down. Monitoring the degree of vacuum in vacuum chamber is another checking system related to the hydrogen hazard. Lack of vacuum in the vacuum chamber causes also the reactor shutdown and the flooding of helium gas into the

Table 2. Measuring, controlling and reactor-link instruments
of a cold neutron source with a closed-thermosiphon.

	Item	Measuring instruments			Controls for liq. level	Display			Sequence	
		Indication	Setting	Type		Meter & (or) recorder	Lamp	Alarm	Shut down	
									He refrig.	Reactor
Bulk of CNS	D ₂ gas tank	Pressure		Pressure transducer [Dielectric gage]	P I D Processor	○				
			Upper limit				○	○	○	○
			Lower limit				○	○	○	○
	Vacuum chamber	Vacuum		Thermo-couple & Penning vac. gage		○				
			Lowest limit				○	○	○ (He gas charge)	○
			Lower limit				○	○	○	○
	Coolant of moderator cell [He gas]	Pressure in vac. chamber	Upper limit	Diaphragm		○	○	○		○
			Lower limit				○	○		○
	D ₂ condenser	Temperature of He refrigerant at inlet		Bourdon tube gage		○				
			Lower limit				○	○	○ [Refrigerant by-pass]	
	Non failure power supply		Loss				○	○	Charging He gas in vac. chamb. ○	○
He refrigerator	Turbine	Speed		Magnetic pick up		○				
			Upper limit				○	○	○	
He compressor		Brake temperature		Thermo-couple		○				
			Upper limit				○	○	○	
		Discharge pressure		Bourdon tube gage		○				
			Upper limit				○	○	○	
		Flow rate of water		Differential pressure sensor						
			Lower limit				○	○	○	
		Oil temperature		Thermocouple gage		○				
			Upper limit				○	○	○	

vacuum chamber.

The cooling system of the moderator cell provides enough cooling of the moderator cell even when the CNS is stopped and the reactor is operating. The absence of adequate cooling of the moderator cell will result in the automatic shutdown of the reactor.

Reactor shutdown caused by the CNS is actuated with a proper time delay after malfunctions. Two-out-of-three instrumentation is used in these essential sequences. The essential control circuits are operated by the uninterruptible power supply system if the normal power lines is failed. This system consists of the oscillator-amplifier inverter(D.C. to A.C. converter) and a battery. The failure of this system causes the reactor shutdown.

The instrumentation, controls and links to the reactor indispensable to the reactor CNS are summarized in table 2.

V. REFERENCES

1. T.Kawai,M.Utsuro,Y.Maeda,T.Ebisawa,T.Akiyoshi,H.Yamaoka and S.Okamoto, " Self-regulating characteristics of a cold neutron source with a closed-thermosiphon" Nucl. Instrum. Methods,A276, 408(1989).
2. T.Kawai,M.Utsuro and S.Okamoto, "Numerical simulation of self-regulating characteristics of a cold neutron source with a closed-thermosiphon" Nucl. Instrum. Methods, A285,520(1989).
3. T.Kawai,M.Utsuro,Y.Maeda,T.Akiyoshi,T.Ebisawa,H.Yamaoka, S.Okamoto and H.Yoshiki, "The instrumental developments for researches on neutron physics at the KUR(5MW)" Proc. Int. Conf. on Neutron Physics, Kiev, USSR, Sept. 14-16, 1987, ed. B. D. Kuzyminov, vol.4, 79(1988).
4. T.Kawai, " Thermodynamic considerations of a closed-thermosiphon type cold neutron source by a discontinuous model" Cryogenic Eng., 23,357(1988)(in Japanese).

Instrumentation & Controls at Reactor Cold Neutron Sources (Including Links to Reactor Controls)

Takeshi Kawai

Questions/Answers/Comments

(C. Eberle)

Question:

Why would one need to handle liquid oxygen around a cold neutron source?

Answer:

Because the liquid oxygen or solid oxygen accumulates when the air intrudes into the hydrogen system while the refrigerator is in operation.

Hydrogen Safety

Wayne R. Frazier

**Chief, Operational Safety Branch
Safety Division**

**Office of Safety, Reliability, Maintainability and Quality Assurance
National Aeronautics and Space Administration**

ABSTRACT

The NASA experience with hydrogen began in the 1950s when the National Advisory Committee on Aeronautics (NACA) research on rocket fuels was inherited by the newly formed National Aeronautics and Space Administration (NASA). Initial emphasis on the use of hydrogen as a fuel for high-altitude probes, satellites, and aircraft limited the available data on hydrogen hazards to small quantities of hydrogen. NASA began to use hydrogen as the principal liquid propellant for launch vehicles and quickly determined the need for hydrogen safety documentation to support design and operational requirements. The resulting NASA approach to hydrogen safety requires a joint effort by design and safety engineering to address hydrogen hazards and develop procedures for safe operation of equipment and facilities. NASA also determined the need for rigorous training and certification programs for personnel involved with hydrogen use. NASA's current use of hydrogen is mainly for large heavy-lift vehicle propulsion, which necessitates storage of large quantities for fueling space shots and for testing. Future use will involve new applications such as thermal imaging.

I. HISTORICAL PERSPECTIVE

The NASA experience with hydrogen safety dates back to the 1950s when the National Advisory Committee for Aeronautics (NACA)--the forerunner of NASA--began to use hydrogen as a fuel. As early as 1954, the research conducted at the NACA-sponsored Lewis Laboratory confirmed the potential of hydrogen as an aircraft fuel and demonstrated its safe application. Further research by the U.S. Air Force, which was seeking improvements in the performance of high altitude aircraft, contributed to the understanding of hydrogen as a fuel.

During the mid-1950s, the national effort by NACA and the military to develop a hydrogen-fueled aircraft produced liquid hydrogen plants and test sites that later provided the technology and facilities to produce hydrogen in quantity. This capability proved to be invaluable to the emerging space program by providing a ready-to-use process for mass hydrogen fuel production, saving years of research and development.

The National Aeronautics and Space Act of 1958 formally established the National Aeronautics and Space Administration (NASA) as the civilian component of the national space program, absorbing NACA as its nucleus. The new organization, which had inherited the Lewis Laboratory, intensified research on liquid hydrogen and oxygen as high energy fuel for rocket propulsion. Lewis Laboratory subsequently developed the first operational cryogenic rocket engine for use in the Centaur upper stage space vehicle.

NASA's long-range plan included the development of launch vehicles capable of orbital, lunar, and deep space missions. As the size and weight of the rockets increased, greater power was needed for launch. Saturn 1 became the first major NASA launch vehicle to use enormous quantities of liquid hydrogen/oxygen mix as the propellant. The Saturn booster was selected as the primary heavy-lift launch platform and, ultimately, was used for the successful Apollo moon missions in the 1960s and 1970s. Today, over 385,000 gallons of liquid hydrogen are mixed with liquid oxygen to power the Space Shuttle Main Engines (SSMEs) when boosting the 180,000-pound Space Shuttle into orbit.

II. HAZARDS OF LH₂/GH₂ IN NASA APPLICATIONS

Liquid hydrogen and gaseous hydrogen require great care in the design of facilities and procedures to minimize operational risk. Liquid hydrogen is a cryogenic with a temperature of -425°F and very high volatility (-423°F boiling point). Gaseous hydrogen has a flammability range (% of hydrogen in air) of 4 to 75, an auto-ignition temperature of 1065° to 1070°F, a minimum spark energy requirement for ignition of 1.6×10^{-8} Btu at 14.7 psia (similar to methane or gasoline), and a rather unusual characteristic known as the Joules-Thomson effect (heat created by rapid hydrogen gas expansion).

In using liquid hydrogen as a propellant, NASA confronts the same basic hazards that are inherent in any laboratory or industrial application of this cryogenic liquid. A critical factor for NASA, however, is the high flow rate requirements for Space Shuttle fueling and lift-off. During "fast fill" fueling operations, flow rates of 10,000 *gal/min* can be achieved. At launch, Space Shuttle Main Engines require over 47,000 gallons of LH₂ *per minute* to provide full power.

The major hazards of fire, explosion, and accumulation from either liquid or gaseous hydrogen are addressed in the basic hardware design. The personnel hazards of frostbite and burns through contact with liquid hydrogen or "boiloff" vapor as well as asphyxiation (oxygen displacement by hydrogen) from exposure to gaseous hydrogen, are addressed through intensive training programs.

III. NASA APPROACH TO HYDROGEN SAFETY

Basic NASA policy requires liquid and gaseous hydrogen to be stored, handled, and used in accordance with stringent safety procedures to avoid jeopardizing life and health, and to minimize risk to property.

The two main components of NASA's strategy to control the hazards associated with hydrogen use are design requirements and operational requirements. The NASA design requirements comprise measures to prevent hydrogen leaks (the primary safety objective),

eliminate ignition sources, install detection systems, and provide ventilation to prevent hydrogen accumulation. The operational requirements stipulate the use of NASA standard operating procedures (SOPs) for all processes, cleanliness requirements, personnel training and certification programs, and development of emergency procedures for all conceivable leak or spill situations.

Design Requirements

Hazard Analysis. To meet NASA standards for hydrogen system safety, the design engineers work with the safety engineers to integrate the design and hazard analysis processes. Safety hazard analyses provide key information that is used to design safe systems. These analyses are incorporated in each stage of a program from concept through development, test, and operation. The action items developed as a result of these hazard analyses are a continuous input to the designers and as a result hazards are engineered out of the system during the design process instead of controlled in the operational stage, resulting in cost benefits and safer systems.

During the conceptual stage of the design process, a preliminary hazard analysis is completed and presented at the preliminary design review (PDR). A more detailed hazards analysis is begun immediately following the PDR as the design matures to address such factors as materials safety, exposure potentials, fail safe requirements, and design redundancy. (Redundancy assures that a single item failure will not cause a functional failure.) The detailed hazards analysis must be completed prior to the critical design review (CDR). The operational hazards analysis (OHA) can be started at this time as procedures and operating instructions are developed but must be approved prior to start of operations. The operational hazards analysis then becomes a "living" document that is changed and modified as tests and operations change.

Materials and Fabrication. The properties of liquid hydrogen impose specific design requirements for materials and fabrication. Particular attention must be given to selecting materials for liquid-hydrogen use. For example, metals must be selected to minimize hydrogen embrittlement [nickel, austenitic stainless steels (304N,316,309S), or aluminum

alloys (2011,2024)]. Also, thermal expansion and fatigue life of materials must be considered. In addition, special lubricants for O-rings (Dupont Krytox 240AC, Dow Corning DC-33) must be used and gas erosion susceptibility must be considered in the selection of non-metals.

Fabrication of hardware for use with cryogenic materials requires special techniques such as using welded joints (ANSI B31.10), wherever possible to prevent leaks and vacuum jackets for liquid-hydrogen lines. A crucial fabrication concern is pressure relief for piping and containers (the pressure of a trapped volume of liquid hydrogen at 14.7 psia, when raised to 70 degrees Fahrenheit, rises to 28,000 psia). NASA also uses supplemental pressure-relief devices to provide redundant protection.

Facilities. Design of a NASA hydrogen-use facility entails incorporating concepts that are not normally considered in conventional construction. The following concepts represent a sampling of these design considerations:

- a. Walls and roofs should consist of light, noncombustible material; limit the accumulation of static electricity; and be fastened to blow out, without collapse of the structure, at an internal pressure of 25 lb/ft².
- b. Electrical wiring and equipment located within 25 feet of connection points must conform with the National Fire Prevention Association (NFPA) regulations (National Electric Code) Class 1 Group B, Division 1 or 2.
- c. Heat should be supplied by passive means (such as through steam and hot water).
- d. Ventilation must be provided in amounts adequate to prevent the formation of flammable concentrations of hydrogen. NASA requires a flow rate of 2 ft³/min per square foot of floor area with the hydrogen detection system capable of sensing hydrogen concentrations that are 20 percent of the lower

flammability limit and 1 ft³/min if the system will detect concentrations at less than 20 percent.

- e. Building or equipment design must avoid inverted pockets that can trap hydrogen gas.
- f. Within a multi-function building, areas designated for hydrogen use should not provide paths for hydrogen leakage to other parts of the facility.
- g. Roadways or surfaces beneath liquid hydrogen piping, from which liquid air might drip, must be noncombustible.
- h. Liquid hydrogen storage devices must be vented to atmosphere. Vent stacks must be placed to avoid contamination of building air intakes. Unused/unburned hydrogen from .25 to .50 lb/sec can be vented from a single vent, which must be at least 16 feet above the roof peak. Larger quantities are best disposed of in a "burnoff" system that is installed in a remote area (200 feet) and equipped with multiple burner arrangements. Stack discharge velocities should be from 20 to 30 percent of the sonic velocity to preclude fires or explosions in the flare stacks.
- i. Hydrogen detection equipment, which must be on line at all times, is designed to function before a hazardous accumulation can form. This equipment must be installed at any point where hydrogen might spill, leak, or accumulate. Whenever possible, the equipment should activate automatic shutoff of the hydrogen source in the event of an accident.
- j. Flame detectors, operating in the infrared and ultraviolet spectrums, should be used to detect hydrogen fires since the flame is essentially invisible.
- k. NASA does not recommend the installation of dikes or containments at liquid hydrogen storage sites. Recent studies indicate that unconfined spills

maximize the dispersion mechanisms provided by spill- and vaporization-induced turbulence that rapidly warms the cloud, making it buoyant.

Siting. The physical location or siting of storage and transfer facilities is a major consideration in the selection of launch pads, laboratories, and test facilities. When compared to liquid hydrogen use in the laboratory environment, NASA must consider the much greater risks of liquid hydrogen and liquid oxygen spill combinations. The U.S. Department of Defense explosive quantity-distance standards are used to site all liquid hydrogen storage facilities to minimize overpressure and fragmentation risks to inhabited buildings, public traffic routes, and other hazardous materials storage due to explosion or deflagration.

Ignition Sources. The elimination of ignition sources is a design consideration that provides protection when the facility fails or procedures are not followed and a spill occurs. Potential ignition sources include:

- a. Electrical sparks - from multiple sources such as lighting, thermostats, motor commutators, and connecting/disconnecting electrical cords
- b. Static electricity sparks - from common occurrences such as combing one's hair or walking on dry ground while wearing synthetic clothing, moving leather belts on machinery, flowing gaseous or liquid hydrogen, turbulence in containers of hydrogen, and induced charges from electrical storms
- c. Friction or impact sparks - including particles of burning metal or stone sheared off when hard objects collide
- d. Hot objects - such as heating elements, flames, and ignited materials

Most electrical and static spark ignition sources can be eliminated through design features such as the use of explosion-proof electrical fixtures, lightning protection systems, conductive flooring, and grounding of all parts of the hydrogen system. Hazards from hot objects can

be controlled through operational procedures such as establishing exclusion zones (limited access) around hydrogen operations and prohibiting smoking or carrying of spark-producing devices into the exclusion areas.

Operational Requirements

Standard Operating Procedures. NASA operational procedures for hydrogen use include detailed actions necessary to accomplish an operation, which is key to safe handling. NASA SOPs are subjected to the same rigorous safety hazard analyses as applied to systems design. For example, SOPs specify that a rigorous cleaning process be accomplished prior to placing a hydrogen system into operation. The procedures identify the cleaning materials, methods to be used to verify surface cleanliness, specific system components to be inspected for contamination (valve seats and stem seals), and filter regeneration among other items. The cleaning procedure will require a warm system flush with 1,1,1-trichloroethane followed by drying and then flushing with demineralized water. This gross cleaning is followed by three cycles of evacuation and purging through a cold trap until no further collection shows. During this process, the system should be "cold shocked" with liquid nitrogen to break loose any attached particles that will be flushed into filters by the liquid nitrogen. If the system cannot withstand a vacuum, drying may be accomplished by flowing hot nitrogen, well above 212°F, through the system. The cleaning requirement is critical to safe operation given the serious hazard that results when liquid hydrogen is contaminated by solid air. In this circumstance, contaminated hydrogen forms an explosive mixture and could be ignited.

NASA operating procedures, in addition to detailing the necessary steps for system operation, include a description of exclusion areas and the maximum number of personnel allowed in such areas; personnel protective clothing (foot protection to prevent skin contact with hydrogen, leather gloves, face shields or other eye protection, and clothing to prevent contact with uninsulated pipes or vessels); purging procedures; first-aid procedures; and emergency procedures. Fire actions might include automatic shutdown of the hydrogen system, use of deluge systems to cool hydrogen containing equipment and extinguish

secondary fires, and use of dry chemicals/ CO_2 /water to extinguish the hydrogen fire *after* the flow is stopped.

Training. To satisfy NASA requirements for safe hydrogen operations, personnel are thoroughly trained in safety and operational procedures. The primary objective of NASA training and certification programs is to ensure that personnel understand the hazards of hydrogen, and are proficient in executing standard and emergency procedures.

Hydrogen safety training is paramount because of the unique dangers that hydrogen presents to personnel. In addition to the obvious hazards (explosion/fire or freezing from direct exposure to the liquid or vapor), hydrogen leaks can produce a lethal environment from oxygen displacement. If the displacement is gradual, the individual could be lulled into a false sense of security, which could preclude self-rescue. If exposed suddenly to a pure hydrogen atmosphere such as when entering a contaminated area or improperly purged storage tank, immediate unconsciousness would occur; the individual would expire within minutes if not resuscitated. Daylight hydrogen leaks are particularly hazardous if ignited because of the difficulty in detecting flame. Special detectors are required to sense these fires and alert personnel.

NASA training is not limited to hydrogen system operators, it also can include personnel involved in the design and construction of the system. A representative listing of training program topics includes operating standards and regulatory codes, safety features, operating controls, fail-safe features, system design, safety reviews and evaluations, and waiver provisions. Operators are certified for operation of liquid and gaseous hydrogen systems. NASA requires annual retraining to retain certification.

IV. PRACTICAL LESSONS LEARNED

Causes

NASA's hydrogen operations have proven extremely safe considering the enormous quantities of LH_2 involved. A study of 96 mishaps derived from all phases of hydrogen

operations were analyzed. The following indicates the approximate percentage of mishaps caused by specific types of deficiencies:

- a. Work area deficiencies - 26 percent (lack of training or inadequate working conditions during installation, fabrication, or cleaning)
- b. Procedural deficiencies - 25 percent (inadequate procedures or failure to follow established procedures)
- c. Design deficiencies - 22 percent (inadequate component or system design)
- d. Planning deficiencies - 14 percent (failure to develop test plans or perform hazard analysis)
- e. Malfunctions and material deficiencies were responsible for the remainder of the mishaps.

Looking at the data from a slightly different perspective showed that valve malfunctions or leaks were involved in over 20 percent of the mishaps. It is interesting to note that the majority of leaks were caused by personnel not following prescribed procedures when applying pressure to, purging, or opening/closing valves. To a large extent, failure to follow procedures or lack of specific instructions was responsible for mishaps that involved leaking connections.

It was found that 83 percent of the mishaps involved a release of hydrogen or LH₂ into either the atmosphere or enclosed areas. Ignition occurred in 60 percent of the atmosphere releases and 100 percent of the enclosed releases.

Improper system purging appears to be a major cause of mishaps. Twenty-five percent of the total were associated with a purging problem; that is, the system was not purged as prescribed or the exit gas was not analyzed to ensure system purity.

In some cases, air introduced into the LH_2 system either through cryopumping or leaks during underpressurization when lines and vessels cooled formed combustible mixtures that detonated.

The safety of road transport for LH_2 is quite high. Of the accidents studied, only five involved highway transportation. Only one accident resulted in a LH_2 spill and there were no ignitions.

Examples

- An explosion occurred in one of the buildings of the Marshall Space Flight Center's test stand 500. An explosion resulted when galvanic corrosion and high pressure caused a gaseous hydrogen leak in an underground pipe. Gaseous hydrogen was trapped under the test stand apron and entered several rooms. The explosion originated in the basement and traveled through connecting ducts to a second room, causing a second explosion.

Specific lessons were learned as a result of this accident: periodic proofing of existing underground lines should be required; existing underground lines installed under roadways should be sleeved and vented; buried lines for use with high pressure propellants should be restricted; active hydrogen sensors should be installed and monitored; and more extensive use of isolation valves, suitable piping, and corrosion protection equipment should be required.

- An explosive accident occurred when a hydrogen tube trailer and an oxygen tube trailer were simultaneously connected to the same manifold. Incorrect purging procedures led to the damage of one shutoff valve and insufficient barriers led to the flow of the higher pressure oxygen into one tube of the hydrogen trailer. Ignition was probably caused by contamination (sand) traveling through a valve at high velocity. There also were several lessons learned as a result of this accident including: development and use of standard operating procedures should be required,

adequate personnel training must be ensured, check valves should be installed, and suitable analysis equipment should be used.

V. NEW RESEARCH

Thermal imaging technology is an accurate and reliable nonintrusive sensing technique used successfully by NASA in earth observations. The concept of using remote sensing techniques to acquire surface temperature measurements with imaging radiometers has been demonstrated successfully at Kennedy Space Center. During and subsequent to the launch of STS-26 (September 1988), the Kennedy Space Center Ice and Debris Inspection team has operated three thermal imaging systems as part of the prelaunch monitoring process.

The NASA Stennis Space Center is sponsoring a program of Thermal Imaging safety applications research and development, which should provide substantive recommendations for various applications by calendar year 1992. Potential uses for this technology include detection, quantification, and assessment of cryogenic gas leaks in the launch environment, during engine testing, and in monitoring storage and transportation vehicles. Potential fire applications include the detection of hydrogen fires that are not visible to the human eye, use of multiple thermal imagers in plume or fire detection to determine area involvement, and evaluation and assistance in fire rescue and emergency egress operations.

VI. CONCLUSION

NASA's experience indicates that hydrogen in any of its forms can be stored, handled, and used safely when the hazards are understood, systems are designed accordingly, and formal operating procedures are followed. The key factors in NASA's successful approach to hydrogen safety are the application of proper engineering practices to the design and construction of facilities, integration of a rigorous safety hazard analysis program into every process phase, and development of standard operating procedures for each operation. NASA training and certification programs are mandatory for all personnel involved in any aspect of hydrogen operations.

VI. REFERENCES

1. NASA Hydrogen Safety Handbook (Draft), National Aeronautics and Space Administration
2. Ordin, P.M., "A Review of Hydrogen Accidents and Incidents in NASA Operations", 9th Intersociety Conversion Engineering Conference, ASME, 1974
3. Los Alamos Scientific Laboratory Progress Report LA-7820-PR, "Critical Review and Assessment of Environmental and Safety Problems in Hydrogen Energy Systems," October 1, 1977--September 30, 1978

Hydrogen Safety

Wayne R. Frazer

Questions/Answers/Comments

(C. West)

Question:

Might the NASA hydrogen safety training programs be open, at least in principle, to workers from US government labs, etc., who are going to be involved in working with hydrogen?

Answer:

Yes, I will provide information on NASA hydrogen training courses and copies of the NASA handbook on hydrogen safety (when published). Also, I will tentatively offer NASA experience to support final safety reviews of the facility.

Regarding training, I will see if some generic aspects of the hydrogen training courses can be extracted.

(P. Ageron)

Question:

What is the pressure reached inside a container (tank or pipe) after an H₂ - air explosion?

Answer:

Of course, the results depend a lot on initial pressures and volumes. Most of NASA experience is on light-weight vessels for flight, so NASA has tested these tanks relative to external explosion.

I am sure I can provide data on the normal range of internal pressures after an explosion, but I don't have that data with me. I will try to provide it as part of the meeting minutes.

Most of NASA ground systems and pipes are designed at least 4:1 ultimate stress to normal operating stress. As a rough estimate, the pressure that explodes a vessel is at least 4 times the maximum working pressure. Over pressure relief devices are set at 100% maximum design pressure, and are sized to limit pressure rise to 10% over 100% maximum design.

(W. Frazer)

Comment:

Note: The following comments were given after the workshop.

Regarding training, NASA Lewis Research Center in Cleveland, Ohio, has developed a hydrogen safety course on the draft version of NASA's Hydrogen Safety Standard. The point of contact is Wayne Thomas (FTS 297-2454, Com (216) 433-2454), who can get one started with the right people to schedule a course.

The internal pressures issue is so complex that I don't think a definitive answer should be given. Of course, the "real" answer depends on the amount of hydrogen available, the percent of mixing with an oxidizer, the initial pressure, the temperature, etc.

Hydrogen Safety

Wayne R. Frazer

Questions/Answers/Comments

(W. Frazer)

Comment (cont.): As a rough cut, NASA and DOD currently use a TNT equivalency of 60% of the LOX/LH₂ combined weight to calculate the explosive effect for less than large quantities (millions of pounds) of LOX/LH₂. However, most NASA and DOD personnel consider this to be excessive with a figure of 10-20% considered more realistic. NASA and DOD are currently performing mixing and explosive equivalency tests at NASA White Sands Test Facility to determine a more true TNT potential. If one wants to "rule of thumb" the pressure based on TNT overpressures, then one could consider all of the H₂ as being involved in the explosion with the proper amount of air and take 20% of the total weight. One can then go to TNT explosive pressure tables and figure the overpressure. Admittedly, this is very rough, but very easy.

The Natural Convection Cooling with Vaporizing Deuterium for the Horizontally Arranged Cold Neutron Source of the HFR - Grenoble

H. Hoffmann

Institut für Reaktorbauelemente
Kernforschungszentrum Karlsruhe, D-7500 Karlsruhe 1, FRG

ABSTRACT

Natural convection of vaporizing Deuterium at 25 K transports the heat generated in the moderator cell of the cold neutron source to a He cooled condenser. The thermohydraulics of this thermosiphon were precalculated and the results verified by experiments in a 1:1 model using D₂ as fluid. The experimental results show that the thermosiphon operates stable. The demanded liquid content of the cell as well as wall temperatures below 50 K can be ensured by a proper design of the cell outlet flow geometry. A 7 min. loss of cryogenic power results in transient temperatures of the cell wall of not more than 300 K.

I. INTRODUCTION

In the High Flux Reactor (HFR) at Grenoble a horizontally arranged cold neutron source is installed that uses liquid deuterium (D₂) as the moderator for cold neutrons. This cold source should provide a high neutron flux, it should be simple in design, and be characterized by high reliability and by safe operation. A high neutron flux calls for installation of the cold source near the HFR core and good moderation requires a D₂ volume of ≥ 5 litres. Hence, the moderator, contained in a horizontally arranged cylindrical cell of 21 cm diameter and 20 cm length, is installed at the end nearest to the core of a horizontal beam tube of roughly 4.5 m length with an inner diameter of only 23 cm (Fig. 1).

Fig. 1. The Cold Neutron Source with Natural Convection Loop (Thermosiphon)

The amount of heat released in the cell is roughly 3 KW, one third being produced in the D_2 and two thirds in the walls of the cell (aluminium). The heat can only be transported if D_2 is allowed to vaporize. This means that the moderator is under conditions of saturation (1.5 bar; 25 K). Hence, D_2 enters the cell as a liquid, vaporizes proportional to the heat generation and leaves the cell as a liquid-vapor mixture. The D_2 vapor is liquefied in a helium cooled condenser positioned well above the horizontal cell axes. The condensate together with the circulating D_2 flow back into the cell. This D_2 circuit is provided as a natural convection loop (thermosiphon). Its driving force results only from the difference in fluid densities within the vertical sections of the tubes connecting the cell and the condenser. The thermosiphon can be realized with separate or concentric tube arrangements connecting the cell and the condenser. Both configurations were investigated. The thermohydraulics of the separate tube arrangement are reported in the references(1,2,3). This paper concentrates on the concentric pipe set-up. In this case D_2 enters the cell in the center tube and leaves the cell via the annulus formed by the center and outer tubes. Fig. 2 shows this flow scheme.

The main problems studied theoretically and experimentally were:

- For physical reasons a D_2 volume ≥ 5 liters is required. This means that for the given cell dimensions the amount of liquid in the cell should be of the order of $\geq 80\%$ of its volume. This must be realized.

Fig. 2. Experimental set-up.

The integrity of the D₂-system must be guaranteed. This necessitates good coolability of the cell walls under steady state and transient conditions. Consequently the cell outlet flow geometry must be properly designed to ensure good wettability of the upper cell walls and hence low temperatures.

The calculation of the natural convection loop calls for the knowledge of the pressure losses of the system components under the specified flow conditions. These pressure losses must be compensated by a sufficiently high liquid column and hence the proper positioning of the condenser.

II. INVESTIGATIONS USING LIQUID DEUTERIUM

Pretests were carried out in air-water flow with simplified model geometries to study the degree of filling in the cell as well as its pressure loss as functions of different operational and geometrical parameters. The main experiments, however, were performed on a 1:1 model of the D₂ loop. The cell wall and the fluid inside the cell were heated to 2500 W and 1500 W, respectively, with a view to simulate power release in the cell wall and the moderator during reactor operation. Instrumentation allowed the determination of the heights of the liquid in the cell and in the loop and the measurement of the temperatures at the cell perimeter as well as of the pressure losses of the thermosiphon components. The D₂ loop was connected to the ILL refrigerator. The operating temperature was 25 K. That is why the components filled with D₂ were insulated by means of a vacuum. For reasons of safety, the test facility was installed on the roof of the ILL refrigerator plant and operated from the control room. The experimental setup is shown in Fig. 2. Measurements were taken both for normal and off-normal operation.

III. RESULTS - NORMAL OPERATION

The temperature of the cell walls were measured as a function of the heating capacity with the loop being filled either completely or partially. The results of these investigations are shown in Fig. 3. The measured temperatures are plotted versus the perimeter of the cell. Up to 3000 W, temperature distribution is homogeneous in the given power interval. At 4000 W, temperature increases up to 70 K in the upper front part of the cell. This can be avoided by a more favorable design of the outlet pipe. At first, this temperature distribution does not vary as the height of the liquid decreases in the loop. In case of a considerable reduction in the liquid contents of the cell, however, excess temperatures as measured under off-normal operating conditions are reached.

Fig. 3. Temperatures measured at the cell perimeter for various cell powers.

Fig. 4. Measured heights of the liquid as a function of the cell power.

The heights of the liquid in the cell were determined as a function of the cell power using capacitive and γ -absorption probes. On the basis of these measurements, the actual mass of the liquid inside the cell can be concluded. However, it is impossible to draw any conclusions concerning the distribution of the liquid and the vapor. The results of these studies are represented in Fig. 4. Obviously, the heights of the liquid

decreases as the power increases. At a cell power of 4000 W, about 80% of the cell is filled, i.e., the degree of filling required is reached.

In Fig. 5, both the pressure drops measured in the system and the results of the preliminary calculations are represented as a function of the cell power. Although similar tendencies can be noticed, differences between calculated and experimental data occur. This is mainly caused by the model for the calculation of the two-phase pressure losses. Compared with the experiment, however, calculation is extremely conservative. The calculated limit values with respect to thermosiphon operation may therefore be exceeded in reality.

Fig. 5. Measured pressure drop in the thermosiphon as a function of the cell power.

IV. RESULTS - OFF-NORMAL OPERATION

As far as safety studies are concerned, knowledge on the temperature distributions during the evaporation of the cell contents is of crucial importance. For this purpose, two series of experimentes were carried out with various liquid levels in the cell⁽¹⁾. In the first series, the contents of the cell was reduced systematically with the refrigerator being in operation. Hence, the condensate resulting form D₂ evaporation was continuously fed into the cell. In the second series, refrigerator failure was simulated by a sudden shutdown for a period of 7 min. Here, the loop was operated under normal conditions, i.e., with a D₂ level of 3 m and a cell power of 3000 W.

Fig. 6. Measured maximum temperatures (T_1) as a function of the vapor dome height for various cell powers

The maximum temperatures measured during the first series of experiments are plotted versus the vapor dome height at various cell powers in Fig. 6. At a cell power of 2000 W, no increase in temperature is observed up to a vapor dome height of about 40 mm. This indicates that excellent cooling of the upper cell wall takes place. Here, the bulk boiling occurs. As the vapor dome height (h) increases, this local temperature is changed rapidly by about 100 K, and, starting from a vapor dome height of about 65 mm, linear increase can be observed. This temperature jump represents film boiling and the transition to mere vapor cooling, which may be concluded from the measured superheating of the vapor. Naturally, the highest temperatures are measured in an empty cell where they amount to nearly 300 K. As the power decreases, smaller maximum temperatures are recorded. To sum up, similar temperature variation patterns can be observed with the temperature jump of film boiling occurring at smaller vapor dome heights.

During refrigerator shutdown, thermosiphon behavior with time is affected by the system pressure, the liquid level in the loop and in the cell and by the temperature distributions of the cell walls. The corresponding investigation results are shown in Fig. 7. When the refrigerator is switched off, the level in the loop decreases rapidly, whereas the system pressure is increased. After about 3 min, the contents of the cell begins to evaporate. About 30 s later, the internal heating system (1000 W) of the cell

Fig. 7. System pressure, liquid level in the loop and in the cell as well as the cell wall temperatures as a function of time during refrigerator shutdown and startup.

is switched off, as this reduction in power also takes place during reactor operation with an evaporated moderator cell. The cell wall temperatures begin to increase as the liquid level in the cell is decreased. Now, thermocouple 1 which is installed at the highest point of the cell also reaches its highest temperature. An empty cell is indicated by the increase in temperature of thermocouple 10 which is located at the lowest point of the cell.

After about 7 min, the refrigerator is switched on again. Cold vapor flows into the cell. The increases in system pressure and temperature are reduced. The production of liquid D_2 is indicated by the decreasing system pressure. First, the liquid D_2 is accumulated in the vertical pipe of the loop. About 26 min after the shutdown of the refrige-

rator, it suddenly flows into the cell. The temperatures of the cell walls are systematically reduced as the degree of filling of the cell increases. After a period of about 35 min, the cell is filled again and wall temperatures of about 35 K are measured by all thermocouples.

V. SUMMARY

Calculations and experiments were performed to study the thermohydraulics of the horizontally arranged Cold Neutron Source of the HFR-Grenoble. It could be demonstrated in D₂-experiments on a 1:1 model that:

- The moderator volume required can be achieved. Under normal operation conditions, 80% of the cell is filled with liquid.
- The increases in temperature at the perimeter of the cell are small when a tube with outlet boreholes on its upper side is used, which extends over the entire length of the cell.
- The thermosiphon function was investigated both under steady state and transient conditions. By comparing calculation and experiment it is noticed that the results obtained for normal operation are conservative. According to the transient investigations, the reactor can be shut down without a scram when a failure occurs in refrigerator operation.

ACKNOWLEDGEMENT

Appreciation is gratefully expressed to Dr. J.M. Astruc for his helpful discussions and to the ILL staff members for their assistance in the realization of these experiments.

REFERENCES

- (1) H. Hoffmann, "Experimental investigations of the heat transfer behaviour of a horizontally arranged cylindrical cold neutron source in a vaporizing deuterium flow", ICEC-10, pp. 390-93, Helsinki 1984.
- (2) H. Hoffmann, J.M. Astruc, "Experimental investigations of the fluid dynamics of a thermosiphon with vaporizing deuterium for a horizontally arranged cylindrical cold neutron source", ICEC-10, pp. 462-65, Helsinki 1984.
- (3) H. Hoffmann, "Natural convection cooling of a cold neutron source with vaporizing deuterium at temperatures of 25 K", Natural Convection: Fundamentals and Applications, eds., S. Kakaç, W. Aung, R. Viscanta, Hemisphere Publishing Corporation, New York, pp. 1140-51, 1985.

The Natural Convection Cooling with Vaporizing Deuterium for the Horizontal Arranged Cold Neutron Source of the HFR - Grenoble

Helmut Hoffman

Questions/Answers/Comments

(T. Kawai)

Question:

In the figure showing the pressure drop versus the heat power, how do you distinguish the two-phase flow from the single-phase flow?

Answer:

In the inlet pipe, we have only a single-phase flow and in the outlet pipe only a two-phase flow. This can be clearly distinguished.

(J. Verdier)

Question:

One advantage of the two-phase return flow in concentric pipes is that it avoids nuclear heating in the inner liquid pipe to form bubbles before entering the cell. Another advantage is that the total mass flow is increased so that the void fraction inside the cell is reduced.

Answer:

Yes, but the void fraction inside the cell is more influenced by the cell outlet flow geometry, and there is no remarkable difference in void fractions for the separate or concentric tube arrangements when comparable outlet flow geometries are used.

(Peter Brewster)

Question:

Does boiling occur in the chamber? Does the liquid density apply?

Answer:

Yes, boiling occurs in the cell. The saturation pressure is 1.5 bar; hence, the respective densities of liquid ρ and vapor ρ_v apply.

(N. Watanabe)

Question:

Is there a minimum necessary height between the moderator and condenser?

Answer:

Yes, this holds for any geometrical arrangement. The necessary minimum height between the moderator and condenser is moderately influenced by the system pressure drop (therefore, the pressure drops and friction factors of all components must be known). The pressure drop depends on the flow rate, the flow rate on the power, etc. Hence, you can only define a minimum height for a given system (power, geometrical arrangement, flow pattern, etc.).

(N. Watanabe)

Question:

At very high-power levels, the inlet liquid deuterium will receive a considerable amount of heat from the outlet two-phase mixture in the case of a coaxial transfer tube. Did you recognize any fluctuation in the inlet flow?

Answer:

The outlet two-phase flow mixture has the same temperature as the inlet flow. Therefore, there is no heat transferred between the two flow passes. No fluctuation was detected in the inlet flow. The flow was very stable.

The Natural Convection Cooling with Vaporizing Deuterium for the Horizontal Arranged Cold Neutron Source of the HFR - Grenoble

Helmut Hoffman

Questions/Answers/Comments

(C. McKibben)

Question:

Is the performance of the CNS dependent on the liquid D₂ return pipe being inside the gas D₂ pipe? This does minimize the subcooling of the liquid D₂ and superheating of gas D₂ - is this important?

Answer:

When the liquid D₂ return pipe is installed inside the gas (2 phase flow) tube, it has the following advantage: heat losses result in bubble formations; hence, at the start of the operation, you get the right flow direction! There is no superheating of the gas and no subcooling of the liquid because the operational conditions are in the saturation state.

Session V

NEW COLD SOURCE PROPOSALS

Chairman

Tasso Springer

1

2

3

4

5

6

7

8

Advanced Neutron Source (ANS)

Colin D. West*

Oak Ridge National Laboratory
Oak Ridge, Tennessee USA

ABSTRACT

The Advanced Neutron Source (ANS) is a new user experimental facility, for all areas of neutron research, planned at the Oak Ridge National Laboratory. An important part of the scientific justification for the project is the provision of world class facilities for neutron scattering work with cold, thermal, and hot neutron beams. Almost two-thirds of the planned instruments are for cold and cool neutron experiments. To provide the beams for these instruments, two liquid deuterium cold sources will be installed in the heavy-water reflector tank of the ANS reactor.

I. INTRODUCTION AND DISCUSSION

The Advanced Neutron Source (ANS) is a new user experimental facility, for all areas of neutron research, planned at the Oak Ridge National Laboratory. An important part of the scientific justification for the project is the provision of world class facilities for neutron scattering work with cold, thermal, and hot neutron beams. Almost two-thirds of the planned instruments are for cold and cool neutron experiments (Fig. 1). To provide the beams for

*Research sponsored by Oak Ridge National Laboratory, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Fig. 1. A preliminary layout of neutron scattering instruments in the beam room and guide hall reflects the importance of cold neutrons in this field of science

these instruments, two liquid deuterium (LD_2) cold sources will be installed in the heavy-water reflector tank of the ANS reactor (Fig. 2).

The reactor is designed to produce an unprecedented thermal flux ($5\text{--}10 \times 10^{19} \text{ m}^{-2}\cdot\text{s}^{-1}$) in the reflector. This will be achieved by a high-power (300- to 350-MW), but very compact ($\sim 70\text{-L}$) core cooled, moderated, and reflected by heavy water. The high power level leads to a very high gamma and

Fig. 2. The ANS reactor core is surrounded by a large reflector tank of heavy water containing beam tubes, irradiation facilities, and two cold sources

neutronic heating rate in components placed close to the high thermal flux region near the core.

Naturally, to get the most intense cold neutron beams, we wish to place the cold sources in as high a thermal flux as possible, which will place a high heat load on the LD₂ and on the aluminum structure of the cryostat. The present cold source design is based on the highly successful vertical cold source at the Institut Laue Langevin (ILL), but the higher power of the ANS reactor will provide a thermal flux for the cold source ~7 times higher. However, with the higher thermal flux goes a higher heat load (Table 1).

TABLE I
Comparison of Cold Source Heat Loads

Cold source	Heat loads (kW)			Unperturbed thermal neutron flux (10 ¹⁹ m ⁻² ·s ⁻¹)
	Structure	LD ₂	Total	
ILL ^a	2.7	3.1	5.8	0.6
ANS ^b	9.5	10.0	19.5	4.6
ANS ^c	8.0	5.8	13.8	3.8

^aVertical cold source before installation of the cavity.

^bAt proposed location ~700 mm from core centerline.

^cAt location where LD₂ heat load approximately matches ILL total heat load (~800 mm from core centerline).

We should like to place the cold source in a thermal flux $\sim 5 \times 10^{19}$ m⁻²·s⁻¹, at which position the heat load would be ~20 kW. The ANS cold source design places gaseous helium cooling channels in the inner wall of the cryostat (Fig. 3); with this system the structure is separately cooled, and only the nuclear and gamma heat deposited directly in the LD₂ is to be removed by boiling and recondensing the cryogen (Fig. 4). Even so, at the preferred position of the ANS cold source, the 10-kW heat load in the LD₂ is ~70% greater than the heat removed from the ILL source by boiling; in the ILL source, both structural and LD₂ heating are removed by boiling. Tests are planned, in the first place with a liquid nitrogen (LN₂) simulator, to help

Fig. 3. A separate system provides forced convection cooling of the cryostat wall with low-temperature gaseous helium

Fig. 4. The heat deposited in the LD_2 is removed by boiling, with the D_2 reliquified in an overhead condenser

determine if this heat load can be removed without thermal-hydraulic instabilities or excessive voiding in the cryogen.

The fallback position is to move the cold sources slightly further away from the core, reducing the heat load on the LD₂ to the same values as the ILL device (Fig. 5): the thermal flux would still be nearly $4 \times 10^{19} \text{ m}^{-2} \cdot \text{s}^{-1}$.

Fig. 5. At the backup location for the ANS cold sources, 800 mm from the reactor core centerline, the heat load on the LD₂ is no higher than on the ILL vertical cold source

Even at this early stage of design, considerable attention has been paid to safety concerns. The design, a simple quasi-steady-state system with no moving parts within the cryostat, will incorporate these redundant and fail-safe features to provide a high degree of safety:

1. full double (at least) pressure boundary containment requiring a double failure before a leak can occur from the system;
2. vacuum annulus between boundaries;
3. no mechanical seals;
4. no condensible purge gas required (vacuum purge will be used);
5. system charged and checked out warm at 0.6 MPa;
6. loss of system cooling that will not require venting of deuterium;

7. R&D program that will address the safety issues through operation of test facilities and, later, a prototype source;
8. diagnostics that will be incorporated into the design to provide assurance that the system safety features are intact;
9. diagnostics and controls that will be tested for reliability and lifetime in the operating environment; and
10. full monitoring of deuterium and vacuum spaces for internal and external boundary leaks.

Neutronics calculations have been benchmarked against experimental measurements on the ILL cold neutron beams and show good agreement (Fig. 6), and the next step will include investigations of different shapes for the cryostat in an effort to find an optimum balance between the effective moderation and reduced heat loads. To avoid the risks associated with hydrogen/deuterium, J. B. Hayter suggested replacing all or part of the LD_2 moderator with liquid nitrogen-15 (LN_2^{15}). According to the neutronics calculations (Fig. 7), LN_2^{15} moderates neutrons well, but to a higher temperature than LD_2 (the freezing points are ~65 K and ~20 K, respectively); the resulting reduction of long wavelength neutron flux is presently judged to be unacceptable.

Fig. 6. The fluxes calculated for the ILL cold source show good agreement with experimental measurements when normalized at a single point

Fig. 7. Replacing the front section of the LD₂ moderator with liquid nitrogen-15 would reduce both the inventory and the heat load of the LD₂ for a relatively small penalty in cold neutron flux

An alternative, presently under consideration, is to use LN₂¹⁵ in the front part of the cold source as a neutron "precooler" and LD₂ behind it, which would reduce the LD₂ inventory and reduce the amount of heat to be removed at 20 K.

Initial tests, with a liquid nitrogen simulator, are planned to verify the thermal-hydraulic behavior of the boiling cryogen. Following are some reasons for these thermal-hydraulic tests.

1. Thermal hydraulics in the boiling moderator at the projected ANS heat loads are somewhat unknown; experiments at ILL and other Laboratories were performed at lower heat loads.
2. Effects of wall heat flux to or from the moderator are unknown.
3. Effects of vessel geometry are unknown.
4. As a result, the stable operating limits are not well known or experimentally demonstrated.

II. SUMMARY

In the ANS facility we plan to include two LD_2 cold sources that will be placed in a thermal flux 6 to 8 times higher than the ILL vertical cold source. The total heat load on the cold sources will be ~3 times higher than the ILL one. Two-thirds of this heat load is deposited in the walls and will be removed by gaseous helium cooling ducts; the remaining one-third, deposited directly in the LD_2 , is about equal to the total heat removed from the ILL cold source by boiling and recondensing the LD_2 moderator.

Neutronics calculations have begun and show good agreement with some existing measured data from ILL. Experimental tests, initially with a liquid nitrogen simulator, are planned.

Appendix

Cryostat Vessel Fabrication

Several methods of vessel fabrication are being considered. The most promising proposal proceeds as follows: (1) form concentric hemispheres from the chosen structural material; (2) weld or braze the two hemispheres together, leaving void spaces where the coolant passages will be, as shown in Figure A1; (3) fill the void spheres with water or other liquid and apply controlled hydraulic pressure to enlarge them, opening coolant passages as shown in Figure A2. This is a commonly used fabrication procedure; the spherical vessel geometry introduces an extra degree of difficulty in the procedure but is not expected to be a serious problem.

Other methods that could be used include machining or die-forming void passages into one of the concentric hemispheres. At present, we believe that the hydraulic method is simpler, less expensive, and requires less structural material. A study will be conducted during detailed design to establish the exact fabrication procedures to be used.

Figure A1. Surfaces after joining and before hydraulic pressurization

Figure A2. Vessel wall after hydraulic pressurization

Advanced Neutron Source (ANS)

Colin D. West

Questions/Answers/Comments

(P. Brewster)

Question:

Are the cooling tubes in the channels spiraled or attached to a header? Is the He flow rate very high?

Answer:

Details of the design are not yet available. The conceptual design only has been prepared. However, to avoid excessive pressure drops, we would probably prefer a header arrangement to a single spiral. The He flow rate is quite high, but not excessively so.

(P. Ageron)

Question:

What is the thickness and the total mass of the Al cell? Why for the same amount of D₂ and Al, is the heat load only 3-4 times higher for a flux 8 times higher?

Answer:

The total mass is of the same order as the ILL vertical cold source, because the ILL device is our reference design. I believe that the lower ratio of heating to power probably results from (a) different-sized design of fuel elements in the ANS; (b) some shielding (fuel side plates plus core-pressure boundary tube is ≈ 20 mm aluminum); and (c) the different position of the cold source.

(P. Egelstaff)

Question:

Mike Rowe suggested that cold source designers quote the ratio of cold source neutron output at (say) 10 Å to that from the best thermal neutron hole on the reactor. What is the Rowe ratio for your source please?

Answer:

Someone in the audience suggested 20 to 30. I will seek an answer to this question as quickly as possible, and try to insert it in the Workshop Proceedings.

(T. Springer)

Question:

What is the expected or possible minimum distance of the guide entrance from the core?

Answer:

In the conceptual design drawing, the guides extend inwards approximately to the reflector tank walls, which in turn are almost 2 m from the vertical core centerline. However, no detailed design has yet been carried out on this issue.

(B. Farnoux)

Question:

What is the estimated lifetime of the cold cell? Is the cold cell a safety barrier?

Answer:

As we learned in Mr. Alexander's presentation, there are few data on irradiation effects at low temperatures, and so the lifetime is unknown. The cold cell must,

Advanced Neutron Source (ANS)

Colin D. West

Questions/Answers/Comments

Answer (cont): therefore, be designed to be removable. In any case, we plan to design the cell as if it were fully brittle.

The outer wall of the cell will be a safety barrier, as in some other cold sources, designed to withstand an atmospheric pressure stoichiometric explosion.

Cold Source Design for the New Munich Reactor

Franz Gallmeier, Erich Steichele

Fakultät für Physik E 21 der Technischen Universität München
D-8046 Garching, BRD

ABSTRACT

A new 20 MW research reactor with an unperturbed thermal flux of 8×10^{14} n/cm² s is being planned in Munich. It will be equipped with a large D₂ cold neutron source. Some design criteria and first calculations on heat input, reactivity reduction and flux depression near the beam tubes at the cold source are discussed.

I. INTRODUCTION

With the project "Forschungsreaktor München - II" (FRM-II) we are planning a new beam tube reactor, which will replace the more than 30 year old FRM-I and which will be a national high flux neutron source mainly for neutron scattering experiments. The reactor with a single, highly enriched and relatively small fuel element will be H₂O-cooled, D₂O-moderated and should produce an unperturbed thermal flux of 8×10^{14} n/cm² s with a thermal power of 20 MW. In Fig. 1 we show the layout of the beam tubes, many of which are large enough to take two or more neutron guides or conventional collimators for two neutron beams.

Fig. 1 Lay-out of beam tubes and secondary neutron sources
 I = vertical cold source, II = optional vertical cold source,
 III = optional hot source

For the production of cold and ultracold neutrons we plan to install a vertical cold source, which serves beam tubes no. 1,2 and 4 and which should have a vertical neutron guide for ultracold neutrons. A second vertical cold source can be installed to serve beam tubes no. 5 and no. 7.

Beam tube no. 5 can accommodate a superfluid liquid helium moderator ("Superthermal Source" [1]) for production of ultracold neutrons. The He moderator looks through a γ -shielding of bismuth onto a standard D₂ cold source. Moreover, the double beam tubes are large enough to take a horizontal cold source as recently realized at the ILL in Grenoble [2] with three guide tubes. In the beginning only the first vertical cold source will be built, but there are several possibilities to meet future demands for more cold neutrons.

II. DESIGN OF THE VERTICAL COLD SOURCE

The D₂O moderator allows the installation of a large deuterium cold source, which is attractive for two reasons: it can better illuminate large beam tube areas and it produces more long wavelength neutrons than a H₂ source. In the present design we plan to use a spherical container for the liquid moderator. With respect to more efficient high neutron guides one could think of a cylindrical D₂ container with a vertical axis instead. However, because of the higher stress in a cylinder than in a sphere one needs thicker walls, which causes higher heat input. For compensation the cylindrical source has to be placed further away from the core and the advantage of possibly better illumination of high neutron guides will be lost because of lower primary neutron flux. We therefore prefer a spherical container of pure aluminum of 1.5 to 2 mm thickness, which can withstand about 2 bar internal pressure.

As a reference value for the diameter of the moderator we choose 36 cm corresponding to a volume of 24 l of liquid deuterium. The results from the recently finished horizontal cold source at the ILL [2] with a volume of only 6 l D₂ indicate, that our source is rather large. However, with respect to three beam tubes looking to the source and the possibility of installing two instead of one re-entrant hole into the source it is not unreasonable.

The position of the cold source has to be optimized with respect to high cold neutron output, low nuclear heating, low reactivity effect and small power density form factors of the core. Some results of our first calculations will be given in the next section.

III. CALCULATIONS

With the neutron and γ -flux distributions as obtained for an unperturbed geometry on the basis of the diffusion code DIFF2D we estimated the heat input into the cold source for different positions of the 24 l D₂ source (2 mm aluminium wall) as shown in Table I:

TABLE I

HEAT INPUT INTO THE COLD SOURCE AT DIFFERENT POSITIONS

Distance Core axis - Cold Source axis [mm]	400	450	500
Total heat input [Watt]	5000	3500	2700
Maximum heat current density [W/cm ²]	1.13	0.92	0.70

These data do not contain small heat inputs from suspension structure materials. The maximum heat current density from the aluminum wall into the liquid D₂ is small enough to avoid film boiling. With a cooling power of 5-6 kW even the close source position might be realized.

The reactivity reduction $\Delta\rho$ caused by the cold source and the neighbouring beam tubes were calculated with the three-dimensional Monte Carlo code MORSE-K [3], which uses 60 energy groups and which allows realistic modelling of complex geometrical structures. Calculations were performed for the 24 l D₂ source at 450 mm and 500 mm distance from the core and for a smaller source of 12 l D₂ at 450 mm distance from the core. We assumed a wall of 6 mm zircaloy for the vakuum container and 2 mm aluminum for the D₂ container. The reactivity reductions for some beam tube arrangements without a cold source are also shown in Table II.

TABLE II

REACTIVITY REDUCTIONS $\Delta\rho$ [%] DUE TO DIFFERENT
COLD SOURCE AND BEAM TUBE ARRANGEMENTS

Distance Core-Cold Source (mm)	450	500
Cold Source 24 l		
$\Delta\rho$ (CNS + BT [1+2+4])	2.23 ± 0.10	1.63 ± 0.08
$\Delta\rho$ (BT [1+2+4])	0.72 ± 0.05	0.43 ± 0.04
$\Delta\rho$ (BT [2])	0.09 ± 0.02	
Cold Source 12 l		
$\Delta\rho$ (CNS + BT [1+4])	1.83 ± 0.08	
$\Delta\rho$ (BT [1+4])	0.59 ± 0.05	

CNS = Cold Neutron Source, BT [1+4] = Beam Tubes no. 1 and no. 4

With the assumption of linear superposition of the reactivity reductions caused by the different systems in the moderator tank we can estimate the reactivity reduction of a big D₂ cold source alone (24 l) at 450 mm distance from the core to be 1.5 % and at 500 mm distance to be 1.20 %; a smaller source with 12 l D₂ at 450 mm distance would cause a reactivity reduction of 1.24 %. When considering the "neutron economy" of different arrangements by these numbers one has to know, that 0.3 % more reactivity corresponds to a nearly one day longer reactor cycle, which is expected to be about 45 days in our core configuration.

Within the first series of calculations we also obtained results on the neutron flux in the cold source and on the flux depression by beam tubes. For the calculations a modified Young-Koppel scattering law was used, where the movement of D₂ molecules in the liquid is described by harmonic oscillations and hindered translations [4]. In the Monte-Carlo

routine the neutron flux was sampled in a "detector volume" either at the surface or in the center of the source. The beam tube windows were 29 x 23 cm², 22 x 19 cm² and 11 cm diameter for beam tubes no. 1, 2 and 4 respectively. Calculations were performed for different configurations, in some of which one "re-entrant hole" was inserted into the source. Results are shown in Table III with errors of typically 5 - 8 %.

TABLE III

COLD NEUTRON FLUX ($\lambda > 2 \text{ \AA}$) FOR DIFFERENT COLD SOURCE AND BEAM TUBE CONFIGURATIONS

Cold source and beam tube configuration	Cold neutron flux ($10^{14} \text{ n/cm}^2\text{s}$)	
	Surface	Center*)
<hr/>		
24 l D ₂ , 450 mm from core		
without beam tubes	3.21	4.58
with BT [1+4]	2.08	3.41
with BT [1+2+4]	1.86	3.15
with BT [1+2+4]+RE	1.15	2.61
12 l D ₂ , 450 mm from core		
without beam tubes	2.79	3.98
with BT [1+4]	1.80	2.90
with BT [1+4]+RE	1.16	2.36
24 l D ₂ , 500 mm from core		
without beam tubes	2.82	3.87
with BT [1+2+4]	1.66	2.73

*) Surface: Sampling volume (~ 8 cm deep) at the cold source surface
Center: Sampling volume (~ 8 cm deep) at the cold source center
BT [1+4]: Beam tube no. 1 and no. 4 installed near the cold source
RE: One re-entrant hole (20 cm ϕ , 9 cm deep) inserted

By comparison of the data obtained for 450 mm and 500 mm source distance from the core one gets a gradient of the cold neutron flux of -2.5%/cm, which corresponds well to the gradient of the thermal flux and which gives a rough idea about the accuracy with which the position of the cold source should be optimized. The gain factor due to the re-entrant hole (flux at the center with re-entrant hole compared to the flux at the surface without re-entrant hole) is about 1.4 for the big source and about 1.35 for the small source. The flux depression at the big source is found to be about 30 - 40 %. This is rather high and certainly the beam tube areas have to be reduced for future optimization.

The data and conclusions reported here give some first ideas on the size and position of the cold source and have to be improved. In future we want to compute with narrower energy groups in the low energy region to obtain better wavelength dependent gain factors. We also want to use another version of the Monte Carlo code (MORSE-SGC), which allows calculations of the neutron current at the beam tube exit.

IV. REFERENCES

1. R. Golub, J.M. Pendlebury, "The Interaction of UCN with liquid Helium and a Superthermal UCN Source", Phys. Lett., **62 A**, 337 (1977).
2. J.M. Astruc, K.H. Gobrecht, "Cryogenics of Cold Neutron Sources", Proceedings of the XVII-th International Congress of Refrigeration, edited by Austrian Association of Refrigeration and Air Conditioning for the Institute of Refrigeration, 177 Bd. Malesherbes, F 75015 Paris, 1988, pp 111-119 (1988).
3. F.A.R. Schmidt, W. Bernnat, "MORSE-K", IKE-Bericht Nr. 4-11, (1972), Institut für Kernenergetik und Energiesysteme, Universität Stuttgart.
4. J. Keinert, J. Sax, "Investigation of Neutron Scattering Dynamics in Liquid Hydrogen and Deuterium for Cold Neutron Sources", Kerntechnik, **51**, 19 (1987).

Cold Source Design for the New Munich Reactor

Erich Steichele

Questions/Answers/Comments

(P. Brewster)

Question:

Can you estimate the cost of the new reactor and the cost of the cold source installations?

Answer:

A two-year-old, preliminary cost estimate was less than 300 Mio DM for the reactor and some infrastructure. The first generation of experimental equipment was estimated at about 70 Mio DM, of which 12 Mio DM are planned for the cold source. This last number is based on the experience from the cold sources at the ILL.

(B. Farnoux)

Question:

What is the distance between the beginning of the neutron guide and the cold source? What is the material of these guides?

Answer:

In the present design, we have assumed a distance of 110 cm, which would mean good illumination of the neutron guides up to a wavelength of 20 Å. We have started to develop metallic mirrors, which can be better cooled than glass mirrors and which are needed for such a short distance between the cold source and the guide tube entrance. The reflecting layer will be ^{58}Ni .

(T. Kawai)

Question:

How much nuclear heating do you account for at the position of the super-thermal UCN source? What kind of thermal shield do you consider for the UCN source?

Answer:

This is a very important question, as it determines the position and, consequently the intensity, of the Superthermal Source. We want to keep the heat input into the superfluid helium less than 300 mW and have therefore shielded the He moderator by 30 cm bismuth between the source and the core and 15 cm lead (or bismuth) around the circumference. Calculations to optimize the shielding are in progress.

Status of the University of Missouri-Columbia Research Reactor Upgrade

*J. Charles McKibben
Chester B. Edwards Jr.
Walter A. Meyer Jr.*
MU Research Reactor
Columbia, Missouri USA

Dr. Soon Sam Kim
Idaho Nuclear Engineering Laboratory
Idaho Falls, Idaho USA

ABSTRACT

The University of Missouri-Columbia (MU) Research Reactor Facility staff is in the process of upgrading the operational and research capabilities of the reactor and associated facilities. The upgrades include an extended life aluminide fuel element, a power increase, improved instrumentation and control equipment, a cold neutron source, a building addition, and improved research instrumentation and equipment. These upgrades will greatly enhance the capabilities of the facility and the research programs. This paper discusses the parts of the upgrade and current status of implementation.

I. INTRODUCTION

The MU Research Reactor (MURR), the highest steady state power university research reactor, is enhancing the research, education, and service capabilities of the facility through a five part upgrade. The existing reactor is a 10 MW, pressurized loop type, already operating at a greater than 90 percent availability to support demand from researchers and industry. The upgrade is focused to meet the increasing demand for more neutrons and higher specific activity radioisotopes, especially for the biomedical community, cold neutrons, and expanded laboratory and office space. This kind of upgrade is especially important at a university research reactor to

help meet the need for increased education and training in the nuclear sciences in the USA. The upgrade includes an extended life fuel element, power increase, instrument and control and electrical system upgrade, cold neutron source (CNS), building addition, and modernization of research instrumentation and equipment.

MURR has been working on this upgrade since 1983, when work started on the fuel element conceptual design and power upgrade feasibility study. The fuel design and safety analyses were performed by the MURR staff. They are also working on the power upgrade safety analyses with support from the MU Nuclear Engineering Program faculty and students. Stone and Webster Engineering Corporation was architect/engineer for the conceptual design, completed in 1987, of the fluid system modifications for power increase, instrumentation and control, and electrical package and the building addition. Stone and Webster acted as MU's agent in determining the CNS options. In March 1989, Sverdrup Corporation was selected architect/engineer for the detail design of the building addition with the design to be completed after a new MURR Director is hired.

II. DISCUSSION

Extended Life Fuel Element

MURR based the new fuel element design on the extended life aluminide fuel (ELAF)⁽¹⁾ with the goal of reducing the fuel cycle cost and providing a core capable of operating at a higher power level. The ELAF is aluminide fuel with UAl_2 the primary constituent in the UAl_x powder with 50 volume percent UAl_x powder in the fuel meat. This gives a loading density of 3 gm/cm³ of high enriched uranium (HEU). The advantage of the ELAF is the coupling of the high uranium loading with the ability to maintain good fuel plate integrity in high burnup conditions. Test plates were run in the Advanced Test Reactor (ATR) in Idaho with peak burnups of 3.0×10^{21} fissions/cm³.⁽²⁾

The uranium loading per unit volume is varied to flatten the radial power density, with a total element loading of 1.244 kg of U-235. Boron carbide is used in some of the inner and outer plates as a burnable poison. The combination of heavy uranium loading, high burnup limit, and flattened power density provides the characteristics needed to more than double the megawatt days (MWD) of energy obtained per element to 300 MWD.⁽³⁻⁴⁾

Since submitting the fuel license amendment in September 1986, MURR has answered three sets of questions concerning the requested license amendment to cover the ELAF fuel. The last set (submitted February 1989) was strictly concerning reactivity transient analysis and some clarification of wording in previous submittals. The Nuclear Regulatory Commission (NRC) asked four more question in November 1989 requesting MURR modify the requested license amendment to better fit the analysis completed for the first three NRC question sets. Response to these latest questions will be completed in March 1990, and the NRC's approval for use of ELAF may be given shortly thereafter. If the DOE university fuel budget can support the startup cost for fabrication of a new fuel design, the MURR ELAF fuel element will be used starting in 1990.

Power Increase

The goal of the power upgrade is to operate the reactor at the maximum safe technical limit as is often done in European reactors. With its flattened power distribution, the new fuel element design provides the greatest increase in the safe technical limits. The physical dimensions are identical to the current fuel element, requiring no change in the geometry of the reactor core.

The only modifications planned for operating at a higher power are the slight increases in operating pressure and primary coolant flow rate, and installation of new heat removal equipment. The upgrade power level has been targeted at 30 MW. The safety analyses performed have shown no problem operating at 30 MW.⁽⁵⁻⁹⁾ However, the loss of coolant accident results are very sensitive to changes in power level around 30 MW.⁽¹⁰⁾ To show confidence in the RELAP5/MOD2 analysis for a low pressure/low temperature fuel plate type research reactor, MU's NE department and MURR submitted a proposal to DOE for a benchmark experiment. This was funded in November 1988 and the work is in progress.⁽¹¹⁾

Reactor Instrumentation & Control and Electrical System Upgrade

The reactor instrumentation and control (I&C) system was reviewed to determine necessary modifications and recommendations for equipment replacement and improvements. An evaluation was performed both for reliability/availability improvements and for reactor upgrade requirements.

During FY89, the first phase of I&C/electrical upgrade began. A small building addition adjoined to the facility houses the new 275 KW Cummins diesel emergency generator. It includes an empty bay sized for the future installation of a 2500 KW electrical substation required for the power

upgrade, CNS, and expansion of facilities. The electrical upgrade also included the installation of a Solidstate Controls Inc. (SCI) uninterruptable power supply (UPS) to handle the reactor I&C system. The emergency generator was put in service in August 1989 and the UPS in November 1989. Upgrade of two I&C subsystems was started during Spring 1989--the area radiation monitoring system (ARMS) and the exhaust stack radiation monitor. The installation of an Eberline analog ARMS will be completed in March 1990 and of a Nuclear Measurements Corporation (NMC) stack monitor in May 1990. MURR is planning to complete the next task in the I&C upgrade during 1990 by replacing the nuclear instrumentation systems (replace six 1960 model channels with three 1990 model channels).

Cold Neutron Source

To meet the rapidly increasing demand for long wavelength neutrons, the MURR upgrade includes adding a cold neutron source (CNS) facility. The CNS will be in the reflector near the core, and this section of the reflector will be modified to enhance the CNS effectiveness. With the reactor operating at 30 MW, the thermal flux around the CNS would be a little more than 3×10^{14} neutrons/cm² sec with the current reflector materials or 6×10^{14} neutrons/cm² sec with a beryllium wedge around the CNS. In either case the gamma heating will be 3.6 watts/gram. The fast flux would be approximately 1.5×10^{14} neutrons/cm² sec. Only a small part of the analyses have been completed to evaluate what combination of reflector materials (beryllium, D₂O, bismuth, etc.) and which CNS design will give the optimal combination of long wavelength neutron beam intensity, capital and operating costs, and minimum impact on other users of the reactor.⁽¹²⁾ With 30 MW reactor power, a lower core position, and a CNS, the intensity of 8 Å (8×10^{-10} m) wavelength neutrons could increase by a factor of 80.

The MURR staff also evaluated CNS designs from three suppliers of this equipment, Technicatome, Interatom, and AECL. As part of this evaluation, Stone and Webster assisted MU in obtaining conceptual design information and cost data from the three vendors. The design information requested was for a total package including cryogenic and control systems that would be applicable to installation and operation of a CNS at MURR's beamport "E" position. The information was to be based on previous experience, and to include the design parameters and estimate of the expected capability and performance characteristics.

Facilities Expansion

The MURR upgrade includes a 44,000 sq ft (4087 m²) building addition, the conceptual design of which was completed in January 1987. The addition centers around a cold neutron guide hall that allows a 60 m flight path for experiments using the CNS. Several electronics laboratories will be relocated in the new addition, freeing up their current location (laboratories with fume hoods) for expanding the radioisotope applications research. The building will also contain a 1600 sq ft (148 m²) counting room, a clean room, culture room and sample preparation laboratory for neutron activation analysis (NAA).

The State of Missouri appropriated \$250,000 for planning of the new addition. Sverdrup Corporation was selected to work on the detail design of this facility in March 1989, but the design will be worked after the new MURR Director is hired. With the July 1989 administrative shift of MURR to the MU campus from the University of Missouri System level, the 1987 conceptual design will be restudied to see if it provides for the best coupling of the combined strengths of MURR and the research strengths of other MU departments.

III. CONCLUSIONS

MURR has designed a fuel element that will cut the fuel cycle cost at least in half and provide a flatter power distribution allowing for a power increase up to 30 MW. A power increase to 30 MW will provide a peak thermal flux of 1.8×10^{15} neutrons/cm² sec in the flux trap and a beam port flux of 3.5×10^{14} neutrons/cm² sec.

The cold neutron source coupled with other improvements will provide an increase up to a factor of 80 in 8 Å wavelength neutrons, which are needed for the fastest growing area of neutron scattering research. The laboratory space available to radioisotope applications for finding ways to cure cancer will at least double. The NAA group will have a major increase in facilities to aid in their trace element research in areas such as nutrition studies, epidemiology studies, archaeometry studies, etc. The 44,000 sq ft (4087 m²) building addition will provide a guide hall and new research facilities to meet the demand for increased utilization of the reactor. Estimated to cost \$23,000,000 in FY88 dollars, the total project will take four to five years to complete.⁽¹³⁻¹⁴⁾ Missouri Governor Ashcroft has pledged the State will provide one-third of the project cost when the matching two-thirds are obtained. The upgrade will expand the world-class capabilities of the best research reactor located on a university campus, and will enable the USA to educate and train the researchers needed by national laboratories and the proposed Advanced Neutron Source.

IV. REFERENCES

1. L.G. Miller and J.M. Beeston, "Fuel Plate and Fusion Insulator Irradiation Test Program," EGG-FT-5273, November 1980.
2. L.G. Miller and J.M. Beeston, "Extended Life Aluminide Fuel Final Report," EGG, June 1986.
3. S.S. Kim and J.C. McKibben, "MURR Upgrade Neutronics Analysis Using AMPX-BOLD VENTURE IV Computational System Benchmarked to the Destructive Analysis of Fuel Element 775F3," September 1986.
4. S.S. Kim and J.C. McKibben, "MURR Upgrade Safety Limit Analysis," September 1986.
5. J.L. Wang, "Analysis of Loss of Flow Accident for MURR 20 MW Power Upgrade Project," MU Master's Thesis, December 1984.
6. J. Tunink, "Analysis of Loss of Pool Coolant for MURR 30 MW Power Upgrade," MU Master's Thesis, 1985.
7. S.S. Kim and J.C. McKibben, "MURR Upgrade Reactivity Transient Analysis," April 1987.
8. C.J. Liao, "Reactor Physics Characteristics of the Current and the Proposed MURR Cores," MU Master's Project, May 1987.
9. B. Donnell, "Criticality Analysis of MURR Spent Fuel Storage Racks and Shipping Cask," MU Master's Thesis, July 1987.
10. J.L. Wang, "Analysis of Loss of Coolant Accident for MURR 30 MW Power Upgrade Project Using Relap5/MOD2," MU PhD Dissertation, December 1987.
11. J.F. Kunze, S.K. Loyalka, R. Hultsch, and J.C. McKibben, "Natural Convection Under Low Temperature and Pressure: Experimental (Benchmark) Verification," DOE Grant DE-FG07 88ER12311, August 1988.
12. W.J. Bohnhoff, "Reflector Materials Evaluation for MURR Upgrade Utilizing the BOLD VENTURE Computer Code System," MU Master's Project, June 1988.
13. "University of Missouri Research Reactor Upgrade," Stone and Webster Engineering Corporation, Boston, March 1987.
14. "Project Implementation Plan Research Reactor Upgrade University of Missouri," Stone and Webster Engineering Corporation, Boston, June 1987.

Status of the University of Missouri-Columbia Research Reactor Upgrade

J. Charles McKibben

Questions/Answers/Comments

(P. Brewster)

Question:

What is the schedule for the upgrade of the core?

Answer:

The fuel licensing will be completed by May 1990. Fuel fabrication will start in 1990. Safety analyses have been completed for the 30-MW upgrade. We are currently working on benchmarking the RELAP5 code for low temperature/low pressure plate-type fuel LOCA analysis. When this is completed, the request for license ammendment will be submitted to the NRC. We have completed about 40% of the instrumentation & control/electrical upgrade.

The CNS-schedule is totally dependent on obtaining additional funds. Hopefully, this can be completed in 1993-94. Building additions and the neutron guide hall will hopefully be funded for construction in 1993-94. Planning funds have been received from the State of Missouri and the building addition is number 2 on the University new building additions priority list.

(T. Kawai)

Question:

In the USA, is the engineering of using Be and Bi at the commercial stage or at the R&D stage?

Answer:

Several US reactors use Be reflectors ATR, HFIR, MURR, etc. NIST (NBSR) uses a Bi and lead gamma shield for the CNS.

New Cold Source for ORPHEE Reactor

P. Breant

Commissariat à l'Energie Atomique
FRANCE

PART TWO FUTURE PROSPECTS

ABSTRACT

We describe the annular source project envisaged in ORPHEE and reactor modifications intended to increase the experimental capabilities in cold neutrons.

I. THE PROBLEM: AN OVERVIEW

The demand for cold neutrons has increased over the past few years. The question is how to find out in what way it is possible to improve the reactor's capabilities in this domain.

In particular, we examined the possibility of installing new guides, making use of two holes made in the leak-tight chamber during construction, one to the north and the other to the east, leaving spaces. The northern hole was located opposite the thermal channel (N°6), and its use would therefore imply construction of a horizontal cold source fully located in the channel. The Eastern hole is placed opposite a cold channel (N°4). On condition, the 2 spectrometers of this channel are moved, a cold neutrons guide could be taken out through this hole. Another cold channel must be created to locate the two spectrometers, which must be moved. This can be done by transforming

channel 1, which is currently a thermal channel, into a cold channel by extending it up to the cold source SF1.

The second solution is currently being studied and should provide the Laboratoire Léon Brillouin (LLB) with new research capabilities by 1992-1993, using cold neutrons.

This solution remains within the global dimensioning of the reactor, which implies no safety studies other than those resulting from the new construction. The construction of a horizontal cold source, and therefore, a third installation would, on the contrary, mean repeating the safety analysis for the entire reactor.

II. GENERAL PROJECT DESIGN: NEUTRONIC AND THERMAL

If we examine a horizontal cross section of the reactor at the core (Figure 1), we see that channels 8 and 1 of the reactor occupy virtually orthogonal positions and are staggered in height by 10 cm. The elongation of the thermal channel (1T) up to cold source N°1 transforms it into a cold channel (1F); therefore it is necessary to design a source of suitable geometry.

The current "flask" shape of the two ORPHEE cold sources must be modified. The cylindrical shape would appear the only acceptable one. The most favorable is the annular cylindrical shape. Paul Ageron, therefore, examined⁽¹⁾ the feasibility of an annular source:

1. In terms of neutronic performance

Using the results of tests carried out on the neutronic model of the Grenoble SILOE reactor, the SILOETTE reactor⁽²⁾.

The design is made with 15 energy groups corresponding to wavelengths between 0.8 and 20 Å.

From this it is deduced that the gain of an annular type cold source 15 mm thick is somewhat better up to 7 Å than the current ORPHEE cold source and becomes worse thereafter, which satisfied the users who tend to work more in the 4 Å range (Figure 2).

2. In terms of thermal performance

Re-evaluating the various energy sources generated in the different structures of an annular geometry source (source effect and target effect), we draw the following conclusions. A global cooling power of between 700 and 1000 watts should suffice to compensate the power generated in the structures of such a source (gamma from the core, beta from captures, and gamma from captures and from fast neutrons), while guaranteeing a margin of overpower comparable to that the installation currently has (approximately 10%).

This result is acquired in the following conditions:

- The cell has maximum height of 30 cm and a diameter of around 130 mm, the liquid hydrogen thickness is 15 mm; and
- It is essential to use light materials: aluminum and magnesium alloy. Use of pure magnesium.

III. FULL SCALE TESTS - QUALIFICATION OF AN ANNULAR COLD SOURCE

In order to verify the above conclusion, the CEA decided to carry out a full scale test during the summer of 1990. To do this, we will take advantage of removing the second ORPHEE cold source to introduce instead, for a few days, a full-scale project prototype.

This source will consist of (Figure 3):

- An external envelope in aluminum-magnesium alloy (3% magnesium) with an external diameter of 128 mm and a thickness of 0.65 mm, formed at the top and bottom of two reinforced 0.7 mm thick ends. The cell will have a height of 220 mm. The hole will be made rigid by installing two thin circumferential stiffeners with a space between to enable free vertical circulation of the boiling point
- A very thin magnesium insert (0.5 mm) intended to define a constant hydrogen thickness. This insert is suitably centered, leak-tight, and full of hydrogen gas, with the reactor in operation.

The total quantity of liquid hydrogen in operation is around 1.4 liters. The construction of the hole is currently being studied, particularly in regards to milling and welding procedures. The total weight of the structures should not exceed 250 g and approximately 100 g of hydrogen. The dimensioning approaches ASME code criteria (section III) - division 1 NC 3200, i.e., for this particular material, a maximum work rate of 53 MPa.

The dimensioning load is as follows:

- Maximum absolute internal pressure of the hydrogen cell, 5 bars;
- Maximum absolute external pressure of the hydrogen cell, 1.1 bar;
- Number of cyclings, 1000; and
- Limit operating temperatures 20 to 380°K.

Qualification of the source will take place with the reactor at rated power using the two installations already in place: a 3-axis spectrometer from channel 4 (reactor hall) and the experimental installations in place on the guides of channel 9.

IV. CONSTRUCTIONS ENVISAGED BETWEEN NOW AND 1992-93

The above qualification will enable optimizing and characterizing of the annular cold source after first comparing calculated evaluations and results. A cold source 30 cm high will be dimensioned.

The CEA will also:

- Modify ORPHEE channel N°1 as needed to transform it into a cold channel
- Design a new channel 4 capable of receiving a large-size guide. A preliminary study has enabled evaluating the possibility of setting up a guide with a cross-section of 12 x 12 cm and evaluating the radioprotection constraints which would result from its installation
- Modify the reactor confinement which enables the above guide to exit the reactor building
- Build a new guide hall facing the eastern zone of the nuclear installation
- Build three new guides stemming from the above guides
- Gradually install 7 new experimental setups, 3 of which are at the end of a guide in order to increase the current ORPHEE capacities by 25 to 30%
- Completely modernize the cryogenerator and cold source's control installation

Thus, in 1993, ORPHEE will have (Figure 4):

4 cold channels distributed as follows:

- 2 oriented towards the west guide hall from which 6 main guides and 3 secondary guides start, capable of holding at least 16 spectrometers
- 1 intended for the utilization of two 3-axis spectrometers inside the reactor building
- 1 with a large cross section oriented towards the East guide hall from which 3 secondary guides start, capable of holding approximately 7 spectrometers
- 2 hot channels and 3 thermal channels will continue to be used, subject to the probable re-arrangement of one thermal channel

Lastly, we note that the envisaged changes do not exhaust our reactor adaptation capabilities.

V. REFERENCES

1. Ageron, P. - Etude de faisabilité d'une source froide annulaire pour deux canaux du réacteur ORPHEE - ILL/89/175 - JUNE 1989. (feasibility study of an annular cold source for two ORPHEE reactor channels)
2. Harig, H. D. - Etude de sources de neutrons froids à hydrogène et deutérium liquides - Thesis at the Université de Grenoble (1967). (Study of liquid hydrogen and deuterium cold neutron sources)

1. core
2. heavy water reflector
3. high-temperature source
4. low-temperature source
5. pool
6. pool inner wall
7. annular space
8. pool outer wall
9. radio-isotope production channel
10. shroud tube
11. vertical irradiation channel

Figure 1.

SOURCES FROIDES

Courbes de gain

Figure 2.

SOURCE FROIDE ORPHEE
- CELLULE ANNULAIRE -

Figure 3.

PROJET DE HALL DES GUIDES EST

Figure 4.

The cold neutron moderator for the continuous spallation neutron source SINQ

F. Atchison, G. Bauer, W. Fischer, K. Skala, H. Spitzer

PAUL SCHERRER INSTITUTE
CH-5232 Villigen-PSI, Switzerland

Abstract

The paper describes the boundary conditions and the resulting design concept of the cold D₂-moderator for the continuous high power spallation neutron source SINQ. Initial thermal-hydraulic calculations performed have shown that the system can be operated safely under the expected load conditions and that also accidental situations such as loss of insulating vacuum do not cause serious safety hazards.

I. INTRODUCTION

SINQ is a spallation neutron source under construction at the Paul-Scherrer- Institute in Switzerland. It will be driven by the proton beam of a high current isochronous cyclotron with a radio-frequency of 51 MHz. This means that SINQ, like most research reactors, will be a cw-neutron source in contrast to most other spallation neutron sources in operation world wide. This has several consequences on the design of the source itself and of its cold neutron moderator.

II. THE SINQ GENERAL CONCEPT AND BOUNDARY CONDITIONS FOR THE COLD MODERATOR DESIGN

Given the fact that SINQ will be a cw-neutron source, the decision was made to make it resemble as closely as possible a research reactor in terms of neutron scattering opportunities. This means that the prime optimization criterion was a high thermal and cold neutron flux and the maximum useful number of horizontal beam ports. This lead to four significant decisions:

1. A large D₂O-tank should be used as neutron moderator
2. A vertical beam injection from underneath into the target was selected to maximize the useful space around the target shield
3. A target of low absorption cross section for thermal neutrons was favoured (liquid Pb-Bi eutectic mixture)
4. Much emphasis was placed on an efficient cold moderator and associated neutron guides.

A vertical cut through the SINQ target station along the direction of the incident proton beam on the left hand side and along the direction of the main axis of the neutron guide system on the right is shown in Fig. 1a. Fig. 1b shows a somewhat enlarged cut through the plane containing the cold moderator inserts.

Fig. 2 gives a horizontal section through the target block showing all beam ports which in fact are on three different levels as indicated by the corresponding numbers.

The neutron production target in the center of the target block will be cooled by natural convection of the Pb-Bi eutectic and hence has a height of almost 4 m to provide enough buoyancy force for the hot liquid. As a consequence, the target becomes very massive and gives good self-shielding for the high energy neutron component in the forward direction of the proton beam. This can be seen from Fig. 3 which gives a polar plot of the neutron intensity in various energy regimes leaving the target. It can also be seen from this plot, that a significant component of high energy neutrons is present which leads to a biological shield much thicker than e.g. with a reactor. This should be as compact as possible. This has two important consequences for the choice of cold moderator concept:

1. Shielding in this direction should remain as compact as possible
2. Significant heating rates and activation of structural components will persist out to quite large distances from the center of the source.

Design provisions have been made on the SINQ D₂O-moderator tank to have both, a H₂ and a D₂-cold moderator available as a long term option. Results of calculations performed for the spectral intensity available at the outer edge of the main shield for the three types of moderators at their projected positions (no effect of neutron guides included) are shown in Fig. 4. In view of these findings, the final decision on the H₂-cold moderator was delayed until operational experience on the source itself and instruments located at its beam tubes are available.

Figure 1: a) Vertical section through the SINQ target station. Section is along the proton injection line on the left and lower half of the right hand side. Upper half of the right side is a cut along the main axis of the neutron guide system.

Figure 1: b) Section through part of the SINQ target block along the plane of the cold moderator inserts. For detailed parts designation see Figs. 7a) and 7b).

Figure 2: Horizontal section through the SINQ target block showing all horizontal penetrations, although on different levels (levels above floor indicated).

Figure 3: Angular distribution of neutrons in different energy bins emerging from the SINQ Pb-Bi liquid metal target. Note the forward self shielding effect!

III. THE GENERAL DESIGN OF THE SINQ COLD D₂-MODERATOR

Given the high energy neutron distribution shown in Fig. 3, it was decided not to place any components of the cold moderator system other than the moderator vessel itself into areas of high radiation fields of fast neutrons. This means that a horizontal insertion port for the cold moderator was foreseen and the heat exchanger of the natural convection system was moved back into a well shielded region. This results in fairly long tubes between the moderator vessel (main heat source) and the heat exchanger (heat sink) and hence requires a large vertical separation of the two to overcome the frictional forces in the tube system by the buoyancy force of the liquid-gas mixture flowing back from the moderator vessel.

Experiments carried out by Hoffmann [1] in conjunction with the development of the second cold moderator at the ILL-reactor [2] showed that such a system could be operated over a large range of heat input. In our case we decided to place the vertical leg partway to the outside of the shielding block for three reasons:

1. The need for shielding behind the horizontal leg would have blocked space valuable for neutron scattering experiments
2. Placing the heat exchanger in the shielding block automatically provides good mechanical protection

Figure 4: Anticipated neutron current at the nominal monochromator positions (6m from the start of the beam tube) for the different moderators of SINQ. The effect of neutron guides is not included.

3. The length of the tube and hence the amount of liquid D_2 as well as the frictional forces could be reduced.

This design implies that the horizontal and vertical leg of the cold source cannot be installed as one unit, but have to be put in place separately with a connection made before the shielding plug behind the horizontal leg can be mounted.

Cryogenic equipment (cold box) and the control system for the source will be placed next to the main shield at a level of 9.5m above ground on top of the neutron guides with a connecting channel to the service areas and to the D_2 -storage tank and parts of the gas handling system, located outside the neutron target hall on the roof of the equipment access building.

A block diagram of the various sub-systems is shown in Fig. 5.

IV. THE COLD MODERATOR SYSTEM

The design of the cold moderator part was governed by the neutronics considerations published elsewhere [3]. In order to avoid rethermalization of cold neutrons upon extraction from the moderator, the cold moderator insertion port will be connected to the neutron extraction port resulting in a T-shaped structure inside the moderator tank, Fig. 6.

Figure 5: Simplified diagram of the various subsystems of the D_2 cold moderator for SINQ. Helium is used for the protective barrier of the D_2 -System only inside the target block. Outside the target block N_2 is used.

Figure 6: Layout of the SINQ-D₂O-Tank with T-shaped structures for cold moderators insertion and neutron extraction to avoid rethermalising D₂O layers.

The mechanical stability of this structure under thermal loads, buoyancy forces and various differential pressure conditions is presently under investigation by computational methods.

The horizontal cold moderator insert is completely independent of this T-structure and has the following main sub-units: (see Fig. 7a)

- a double-walled vacuum jacket with a helium barrier between the outer and the inner tube. The part of the vacuum jacket intruding into the D₂O-tank consists of an outer 2 mm thick AlMg₃-tube and an inner zircalloy tube, 3 to 4 mm thick which is the pressure safety tube and will withstand an internal pressure of 30 bar.
- The source plug, comprising the moderator vessel, the concentric transfer tubes for liquid deuterium (inner tube) and liquid-gas mixture (outer tube) of the heat removal system and a protective support tube which changes to a massive shielding sleeve outside the D₂O tank.
- The shielding and reflector plug comprising a D₂O reflector volume to be located behind the D₂ moderator to minimize losses, its associated D₂O circulation tubes and the cylindrical central shielding plug of the insert.

Fig. 6 also shows the D₂ moderator vessel in the T-shaped tube structure and the D₂O reflector volume which makes up for most of the reflector displacement by the cold source insertion tube.

The moderator vessel itself will be made of 99.5 % pure aluminium, semi-hard with one welding seam around its cylindrical surface at the far end with respect to the target. Material softening by the weld requires that the wall thickness of the vessel be increased from 3 to 5 mm in this region to obtain the desired strength to resist an internal pressure of 30 bar. Fig. 8 shows a vertical cut through the moderator vessel and its concentric D₂-flow tubes. Some relevant data are given in table 1. The vertical leg of the cold moderator system is shown in Fig. 7b. It will be inserted from the top and connections to the horizontal leg will be made inside the connector box where the two inserts meet. This box will afterwards be sealed to connect the insulating vacua of the two inserts. The second flange on the connector box shown in Figs. 7a and 7b completes the protective helium barrier (see below).

The main components of the vertical insert are:

- the vacuum jacket surrounding all cold parts for thermal insulation
- the D₂/He heat exchanger (plate heat exchanger with interconnectors) to remove the total of 2.65 kW of heat load from the D₂ (capacity 3 to 3.5 kW).
- the phase separator located beneath the heat exchanger to remove the liquid from the mixture coming up from the moderator vessel.
- the concentric D₂-transfer tubes ending in the phase separator in such a way that liquid D₂ is flowing downwards in the inner tube and the liquid-gas mixture comes up in the outer tube to a higher level for phase separation

Figure 7: a) Vertical section through the horizontal insert of the SINQ cold D_2 moderator (pipe system, phase separator and heat exchanger)

- the vacuum dome above the heat exchanger where the cold He-transfer tubes and the D₂ gas tube penetrate the cold moderator insulating vacuum space.

The protective barrier system is designed to avoid any possible contact between deuterium and oxygen from the air which could ultimately form an explosive gas mixture. Although the SINQ beam ports are filled with helium which also surrounds the horizontal insert of the cold moderator, it was decided to have a separate additional helium system around the cold part of the D_2 circuit for the following reasons:

- the cold moderator helium barrier will be continuously monitored for oxygen contamination which suggests having as small a volume as possible
- in case of the need for access to the structural parts of the cold moderator system, the beam port helium system needs not be opened.

The helium gas in the protective barrier will be continuously circulated, carefully monitored for pressure loss and contamination by other gases and refrigerated to remove the heat it picks up from the walls in the region of high neutron flux.

Outside the main shield all system parts containing warm D_2 -gas will be surrounded by a N_2 -gas barrier rather than helium for the following reasons:

- N_2 is much cheaper than helium
- Helium is used for leak detection on experimental facilities and thus should be present in the smallest possible amounts in the air
- monitoring for deuterium is easier in nitrogen than in helium

The pressure in the N_2 protective barrier will also be kept at 1.1 bar to avoid oxygen-intake in case of a leak.

VI. THE COLD HELIUM SYSTEM

Refrigeration of the D_2 in the heat exchanger is accomplished by cold helium gas from an existing cold box whose capacity is being upgraded to 3.1 kW. With a total of 2.65 kW to be removed from the D_2 -source, this offers some reserve. The helium will be supplied to the heat exchanger at 19 K and 7.5 bar and will return at 25 K, 7 bar. The cold box will operate at constant cooling power; at reduced source power heat will be provided to the system by auxiliary heaters in the helium circuit. The cold helium transfer line between the cold box and the heat exchanger will be 20 m long each way and will be in a channel inside the target shielding block. Its outer diameter will be 90 - 100 mm.

VII. THERMAL-HYDRAULICS AND ACCIDENT CONSIDERATIONS

In order to be able to predict the behaviour of the cold moderator system under different operating conditions and in case of abnormal situations, a computer model of the D_2 circuit was established.

The model treats the three vessels of the system as "localized capacitors" where phase changes can take place and the mass content can vary. Connecting pipes are treated as "continua" which are subdivided into individual elements. The corresponding coupled partial differential equations are replaced by difference equations and applied to the finite elements. Coexistence of vapor and liquid is allowed in all volumes of the cold part of the system, whereas only vapour exists in the storage tank and the pipe connecting it to the heat exchanger. Dynamical equilibria in mass, energy and forces are established

for all elements and the resulting differential equations are integrated numerically. The compressibility of the vapour as well as of the liquid are taken into account in the whole system.

To date, heat input has been allowed for in the moderator vessel and in the phase separator-heat exchanger volume. An extension to the case where heat input is possible also along the connecting pipes is under preparation.

In order to benchmark the model and to obtain realistic values for some poorly known parameters, the experimental data given by Hoffmann [1] for the ILL-test experiments were verified in a first step.

Based on these results a preliminary series of calculational runs was performed to test the behaviour of our planned system. It could be shown that, when starting from an arbitrary non-constant set of operating parameters (flow velocity in the pipes, heat input at the moderator vessel, liquid-to-vapor ratio etc.), the system moves towards a stable set of values within a few seconds. The operating parameters obtained for the stationary flow conditions are listed in Table 2. These calculations will be continued to obtain a complete picture of the way the system reacts under changing operating conditions.

As a worst case assumption, complete instantaneous loss of the insulating vacuum was considered with a resulting step function like heat input of 30 kW to the moderator vessel and 10 kW to the heat exchanger. Heat input to the pipes has so far been neglected but will be taken into account in the next round, together with a more realistic rise function of the heat input. However, even with these very pessimistic assumptions, the results obtained for the maximum pressure in various parts of the system were very reconciling.

It should be noted that, as a starting situation, both pipes connecting the moderator vessel to the heat exchanger were assumed to be completely filled with liquid at rest (i.e. the spallation source was not operating). Hence, as a consequence of the heat input to the moderator vessel and the resulting vaporization the liquid had to be expelled from the pipes into the heat exchanger where it vaporizes. The resulting pressure as a function of time in the three "capacitor" volumes is shown in Fig. 9. Under the very pessimistic assumptions made here, the pressure in the moderator vessel reaches the design pressure of 3.6 bar for a very short period of time. This shows that, under slightly more realistic assumptions the design pressure of the moderator vessel will not be reached even in case of a very rapid loss of the insulating vacuum. The peak is caused by inertia of the liquid in the connecting pipe and has practically disappeared as soon as the flow velocity of the medium reaches its maximum value at the pipe exit into the phase separator. Fig. 10 shows the flow velocities of the medium (liquid resp. vapour) at the exit point of the moderator vessel and at the entrance point of the storage tank. The delay caused by compression of the medium inside the system (sound velocity) is clearly seen. The diameters of the two pipes and the temperature of the medium are significantly different. Therefore the absolute values of the velocities are not comparable.

Figure 9: Time dependence of the internal pressure at three different positions in the D_2 -system as a result of a sudden heat influx of 30 kW at the moderator vessel and 10 kW at the phase separator. The enlarged scale at the right refers to curves with arrows pointing to the right.

VIII. CONCLUSION

Although still of a somewhat preliminary nature and not yet complete, the calculations performed so far for the design of the SINQ cold moderator system show that the system can easily cope with the expected heat load and is also safe against accidental loss of the insulating vacuum. Nevertheless, in a next step, rupture of the moderator vessel will be considered and the resulting pressure buildup in the vacuum space will be investigated.

IX. ACKNOWLEDGEMENTS

We would like to thank Dr. K. Gobrecht, Dr. H. Hoffmann, C. Doose and E. Krähling for valuable advice during the conceptual design phase and A. Höchli and J. Ulrich for help with the design and supporting interest in the calculation.

Figure 10: Time dependence of mass flow velocity at the exit of the moderator vessel and at the entrance to the storage tank as a result of a sudden heat influx of 30 kW at the moderator vessel and 10 kW at the phase separator. The time delay is clearly visible. The connecting pipes were assumed full of liquid at $t = 0$.

X. REFERENCES

1. H. Hoffmann: "Natural convection of a cold neutron source with vaporizing deuterium at temperatures of 25 K", NATO, Advanced Study Institute: Natural Convention, Fundamentals und Applications, July 16-27, 1984 Izmir Turkey.
2. K. Gobrecht, this conference.
3. F. Atchison, W. Bucher, A. Höchli, I. Horwarth and L. Nordström "The D₂ cold-neutron source for SINQ" in "Advanced Neutron Sources 1988", Institute of Physics Conference Series No. 97, D. K. Hyer, ed. Bristol and New York 1989, pp. 473 - 482.

Total volume	22.3	l
Volume filled with liquid D ₂	~ 20	l
Total mass of Al	4120	g
Total weight of filled vessel	~ 9	kg
Design internal pressure	3.6	bar
Max. operating pressure	2.8	bar

Heat deposition at 1 mA proton current:

front cover	173	W
cylindrical part	67	W
back cover	15	W
deuterium	1250	W
Total	1505	W
Max. surface heat flow	0.2	W cm ²

Table 1: *Some relevant data for the D₂-vessel of the SINQ cold moderator*

Heat load on the moderator + vessel (1.6 mA)	2	kW
Total mass of D ₂ in the moderator vessel	2.9	kg
Mass flow in and out of the moderator vessel	40	g/s
Flow velocity of the liquid gas mixture (forward)	0.2	m/s
Flow velocity of the liquid D ₂ (return)	0.9	m/s
Mass fraction of vapor in the moderator volume	0.2	%
Mass fraction of vapor in the forward flow tube	17.1	%
Pressure in the moderator vessel	1.6	bar
Pressure in the heat exchanger	1.5	bar

Table 2: *Stationary-state operating conditions of the SINQ cold source*

The Cold Neutron Moderator for the Continuous Spallation Neutron Source SINQ

Walter E. Fischer

Questions/Answers/Comments

(T. Springer)

Question:

For the same useful neutron flux, what is the fast spallation neutrons background at the shielding surface, as compared to what you would get at a fission source?

Answer:

The ratio of high-energy neutrons to useful evaporation neutrons for our case is about 1:10. This is a figure that is integrated over the whole space-angle. On the horizontal level (90° to the target), where our neutron extraction devices are, it is less.

(H. J. Roegler)

Question:

At Würenlingen, you had the unique possibility to have an operating medium-flux reactor and an existing accelerator, available for attaching a cold source. Have you compared these two possibilities under cost and performance aspects and why did you decide on spallation?

Answer:

The reactor is an H₂O-reflected, open swimming pool. Installation of a cold source, although possible in principle, would not have been very efficient. Furthermore, only half of the circumference is accessible for neutron extraction.

Since "Saphir" is a very old reactor, possible safety requirements are nearly unpredictable.

(P. Brewster)

Question:

Are there bellows along the aluminum beam tubes inside the D₂O vessel?

Answer:

Yes, they are needed. Detailed design has not been made yet.

(K. Gobrecht)

Question:

Please give the expected heat-load data for the moderator volume?

Answer:

For a primary proton current of 1.5 mA, the heating is the following:

260 W for the front wall of the vessel;

101 W on the cylinder;

23 W on the backside; and

1875 W in the liquid D₂, which sums up to ≈2260W total.

The Cold Neutron Moderator for the Continuous Spallation Neutron Source SINQ

Walter E. Fischer

Questions/Answers/Comments

(P. Egelstaff)

Question:

If you draw a sphere that encloses your liquid D₂ source and is centered on the target center, you obtain a ratio of liquid D₂ volume to the total volume of R. It seems that the ratio R is several times larger in your case than for a reactor such as the ILL or HFR. Can you quote this ratio of ratios please, as it tells us how much more efficient you are than a reactor?

(G. Bauer)

Answer:

The answer is 4 times, for example, this source produces cold neutrons from the target neutrons four times more efficiently than a reactor does.

LANSCCE Upgrade Cold-Sources

Gary J. Russell and Harold Robinson

Los Alamos National Laboratory
Los Alamos, New Mexico USA

ABSTRACT

The present LANSCE target system provides twelve neutron beams for use in basic materials science and nuclear physics research. Four flux-trap moderators produce the neutron beams; there are three chilled (≈ 290 K) light-water moderators and one liquid (≈ 20 K) para-hydrogen moderator. A second experimental hall has recently been added to the original LANSCE facility. To adequately utilize this new experimental hall, four new neutron flight paths (or beamlines) will be added, bringing the total number of flight paths at LANSCE to sixteen. The *LANSCE Upgrade target system* will provide the requisite moderators to simultaneously service the sixteen flight paths. We have not finalized the types of moderators that will be included in the LANSCE Upgrade target system. A new *back-scattering* moderator concept will be employed and is discussed here. Other ideas such as *composite* and *coupled* cold-moderators hold considerable promise for enhancing LANSCE cold-source neutronic performance; these concepts are also addressed.

INTRODUCTION

The Manuel Lujan, Jr. Neutron Scattering Center (LANSCE)¹ is a state-of-the-art, pulsed-spallation neutron source. The present LANSCE target system² is capable of providing neutron beams to twelve flight paths where basic research is done in the areas of materials science and nuclear physics.

Figure 1 depicts the LANSCE Target-Moderator-Reflector-Shield (TMRS) system. Presently, there are four slab-moderators in flux-trap geometry between the split targets. Figure 2 shows the four LANSCE TMRS flux-trap moderators; each moderator services three flight paths. Three of the moderators are chilled (≈ 290 K) light water. Two of the water moderators are heterogeneously poisoned with gadolinium at 2.5 cm from the exit face and have cadmium decoupler/liners. We call these two moderators "high-intensity" moderators. The third water moderator is heterogeneously poisoned with gadolinium at 1.5 cm and has a boron decoupler/liner ($1/e$ transmission at ≈ 3 eV). We refer to this moderator as the "high-resolution" moderator.

The *poison* neutronically defines (for neutrons with energies below some cutoff energy) the thickness of a moderator viewed by an experiment. *Decouplers* surround a moderator and neutronically isolate it (for neutrons below some cutoff energy) from the reflector. *Liners* neutronically isolate the moderator "viewed surface" from the reflector/shield. The type, thickness, and depth of a poison material (together with the types and thicknesses of decoupler and liner materials) determine the time-shape of neutron pulses. The target-system designer of a spallation neutron source must minimize the trade-offs between moderator neutron intensity and time-resolution when maximizing moderator neutronic performance.

We recognize the importance of cold neutrons in condensed matter research; our fourth flux-trap moderator is liquid para-hydrogen at ≈ 20 K. The liquid hydrogen moderator has no poison, a gadolinium decoupler, and a cadmium liner.

A second experimental hall, with an area of 1700 square meters, has been added on the west side of the original LANSCE experimental area (see Fig. 3). To adequately service the new experimental hall with high-quality neutron beams, four new neutron flight paths must be added. Penetrations through the LANSCE bulk shield to service these flight paths have been drilled. Before the four holes were drilled, we had to establish the two moderators servicing them.

One constraint imposed on the two new moderators was that they had to minimally perturb ($< 5\%$) the neutronic performance of the four existing high-performance LANSCE flux-trap moderators. A second constraint was that they also had to be "high-performance" moderators. That is, the absolute neutronic performance of the two new moderators must be at least $\approx 80\%$ of the absolute neutronic performance of the existing LANSCE flux-trap moderators.² These were our *original* goals for the two new moderators; we hope to exceed these goals whenever possible. One technique that will help achieve the neutron-intensity performance goal for the two new moderators is to deploy them in back-scattering geometry as discussed below.

In addition to providing two new moderators, another objective of the LANSCE Upgrade target system is to enhance and optimize the neutronic performance of the four flux-trap moderators. Two possible approaches to improving the neutronic performance of LANSCE flux-trap moderator cold sources have been identified: a) composite cold-moderators, and b) coupled cold-moderators. The neutronics of these two approaches are discussed below.

THE BACK-SCATTERING MODERATOR CONCEPT

The most neutronically efficient spallation target-moderator geometry (in terms of useful neutrons produced per proton striking the target) is a slab-moderator with either a cylindrical or slab target directly opposite the moderator-viewed surface.³ The drawback of such a geometry for a spallation neutron source is the presence of fast (0.1 to 20 MeV) and high-energy (> 20 MeV) neutrons in the extracted neutron beams. These latter two "neutron-beam contaminants" can cause excessive backgrounds in instruments using the neutron beams and may require extreme neutron shielding measures. The unique LANSCE split-target, flux-trap moderator design allows for slab-moderator geometry without excessive fast and high-energy contamination of the extracted neutron beams.

We invented a unique adaptation of the flux-trap moderator scheme, which we refer to as the back-scattering moderator design. Figure 4 depicts the strategy of a back-scattering moderator compared to that employed with flux-trap moderators. For the geometries illustrated in Fig. 4, the back-scattering moderator produces neutron-leakage beams that are $\approx 15\%$ more intense than the flux-trap moderators.

For the LANSCE Upgrade target system, we will place the two new moderators in back-scattering geometry *in front of the upper target* (see Fig. 5). This will allow us to physically accommodate four new neutron beamlines in the LANSCE TMRS and adequately service the new LANSCE experimental hall with neutron beamlines (see Figs. 6 and 7).

COMPOSITE LIQUID PARA-HYDROGEN MODERATOR

We investigated a scheme to improve the neutronic performance of our flux-trap, liquid para-hydrogen cold moderator. This strategy (called a composite moderator) calls for a premoderator (such as water) to be placed between the target void-zone and the liquid hydrogen moderator (see Fig. 8). Several premoderator materials were studied, including water, zirconium hydride, ortho-hydrogen, beryllium, and titanium hydride. Figure 9 depicts the gain in neutron leakage (for energies < 100 meV) with a water premoderator and a liquid para-hydrogen (5 cm thick) moderator. The results are encouraging, with neutron intensity gains of 1.5 being predicted. However, before drawing any general conclusions, the energy-dependency of the gain must be looked at in detail as well as the severity of any attendant neutron-pulse broadening. We will also study the effects of including a premoderator around the other four sides (excluding the face where neutron beams are extracted) of the hydrogen moderator. The premoderator will reduce the heat load in the cold moderator. We will also investigate decoupled premoderators.

For the LANSCE Upgrade target system, we intend to implement the composite moderator (premoderator/moderator) concept to increase the neutron leakage from the LANSCE decoupled flux-trap, liquid para-hydrogen moderator. If it does nothing else, a composite cold-moderator should increase the dynamic range of neutron energies useful to an instrument.

COUPLED LIQUID PARA-HYDROGEN MODERATOR

Russell³ has shown that the neutron leakage from a coupled (the absence of a decoupler and/or liner) flux-trap liquid-hydrogen moderator can be significantly enhanced over that from a decoupled one. However, this neutron intensity increase does not come "free." The price is paid in enlarging the width of the neutron pulses from the moderator. Figure 10 compares the time distribution of leakage neutrons (with energies < 35 meV) from decoupled and coupled liquid para-hydrogen moderators. Figure 11 depicts the time-integrated neutron leakage as a function of time. After ≈ 200 μ s, the neutron leakage from the coupled moderator is about twice that of the decoupled one. Other factors, such as differences in the rise-time of neutron pulses from coupled moderators and decoupled moderators, may be significant and require further study.

COMPARISON OF CALCULATED AND MEASURED NEUTRON SPECTRA

Prael⁴ incorporated into the Los Alamos Monte Carlo code system⁵ the ability to perform point detector computations using thermal neutron-scattering kernels. We employed this powerful capability to predict the neutronic performance of the LANSCE para-hydrogen moderator. Brun⁶ recently measured the absolute neutron spectrum from the LANSCE hydrogen moderator. Figure 12 shows the comparison between calculated and measured neutron leakage spectra. The comparison is reasonable but there is room for improvement. More specifically, the calculation was for 100% para-hydrogen; at least 2.5% ortho-hydrogen should be included in the computation, which will be done. There may be a problem in the asymptotic value of the computed cross section at the higher neutron energies; we will investigate this problem. Further improvements to the scattering kernels are warranted at lower energies; Macfarlane will make some improvement in the liquid-hydrogen scattering kernels at low energies.⁷

CONCLUSIONS

The present LANSCE TMRS can be enhanced with the LANSCE Upgrade target system, which will add two additional moderators and four additional neutron flight paths to the LANSCE facility. This addition will bring to six the number of LANSCE moderators and to sixteen the number of flight paths, which will be serviced simultaneously with neutron beams. The absolute neutronic performance of the two new upgrade-moderators will be at least 80% of the absolute neutronic performance of the existing LANSCE high-performance flux-trap moderators. For the LANSCE Upgrade, we will optimize the neutronic performance of all six moderators to meet experimental requirements.

Composite and coupled liquid para-hydrogen moderators are promising approaches for significantly enhancing the neutronic performance of the present LANSCE flux-trap, liquid para-hydrogen moderator. Both of these approaches will be studied further for LANSCE Upgrade.

Final decisions on the types of moderators (materials, temperatures, poisons, decouplers, liners, coupled, etc.) for LANSCE Upgrade have not been made; these decisions will be driven by experimental requirements. In addition to liquid para-hydrogen, we are looking at liquid methane as a possible cold-source moderator.

Our comparison between calculated and measured absolute neutron leakage spectra from the LANSCE liquid para-hydrogen moderator is encouraging. We are looking into the details of the discrepancies.

ACKNOWLEDGEMENTS

We appreciate the support of Roger Pynn for this work and acknowledge useful discussions with Torben Brun. We thank Tatia Vander Maat for typing and Maria DiStravolo for proofreading the text. LANSCE work is supported by the US Department of Energy, Office of Basic Energy Sciences, under contract W-7405-ENG 36 with the University of California.

REFERENCES

1. R. Pynn, "Recent Progress at LANSCE," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X)*, Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 47-52.
2. G. J. Russell, "LANSCE Target System Performance," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X)*, Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 483-496.
3. G. J. Russell, C. D. Bowman, E. R. Whitaker, H. Robinson, and M. M. Meier, "LANSCE High Power (200 μ A) Target-Moderator-Reflector-Shield," in *ICANS-VIII, Proceedings of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources*, (Rutherford Appleton Laboratory, Chilton Didcot, England) RAL-85-110, pp. 272-293.
4. R. E. Prael, private communication.
5. R. E. Prael and H. Lichtenstein, "User Guide to LCS: The LAHET Code System," Los Alamos National Laboratory report LA-UR-89-3014 (September 1989).
6. T. O. Brun, private communication.
7. R. E. MacFarlane, "Cold Moderator Scattering Kernels," these proceedings.

Fig. 1. Illustration of the LANSCE target system consisting of a split-target, an inner beryllium/nickel reflector region, and an outer nickel reflector/shield. Three water slab-moderators and a liquid hydrogen slab-moderator are in flux-trap geometry between two tungsten targets. The system is one meter in diameter and one meter high.

Fig. 2. Expanded plan-view schematic of the LANSCE target/moderator arrangement. The cold moderator is depicted on the right side.

Fig.3 Illustration of the LANSCE facility, the proton storage ring, and the LANSCE support building. The massive addition of the experimental hall is evident.

TWO FLUX-TRAP
MODERATORS

ONE BACK SCATTERING
MODERATOR

Fig. 4 The back-scattering moderator concept contrasted to the flux-trap moderator approach.

Fig. 5. Illustration of the LANSCE Upgrade target system, showing the two upper back-scattering moderators and four flux-trap moderators. Note that the back-scattering moderators are forward of the upper LANSCE target.

UPPER MODERATORS FOR LANSCE UPGRADE

Fig. 6. Illustration of the upper back-scattering moderators and the new penetrations that have been drilled through the LANSCE bulk shield.

Fig. 7. Plan-view layout of the LANSCE experimental areas 1 and 2. Experimental area 1 is the original target area and experimental area 2 is the new experimental hall addition. The twelve flight paths serviced by the four flux-trap moderators are shown as dotted lines; the four new flight paths serviced by the two back-scattering moderators are depicted as solid lines.

Fig. 8 Illustration of the composite cold-moderator concept. The premoderator is designated as the ambient moderator; the moderator is called the cold moderator. In the scenario shown, the premoderator is coupled to the moderator. Both the premoderator and moderator are decoupled from the reflector.

Fig. 9. The neutron leakage gain of a composite light-water/para-hydrogen cold-moderator to a para-hydrogen moderator as a function of premoderator (water) thickness. The para-hydrogen moderator thickness is fixed at 5 cm.

LANSCCE Liquid Hydrogen Moderator Calculated Neutron Leakage Time Distributions

Fig. 10. Calculated time-distribution of leakage neutrons from decoupled and coupled (100%) para-hydrogen moderators. The decoupler material was gadolinium.

LANSCCE Liquid Hydrogen Moderator Calculated Neutron Leakage Time Distributions

Fig. 11. Computed time-integrated leakage neutron distributions from decoupled and coupled (100%) para-hydrogen moderators. The decoupler material was gadolinium.

Fig. 12. Calculated and measured neutron leakage spectra for the LANSCE para-hydrogen moderator at ≈ 20 K.

LANSCCE Upgrade Cold Sources

Gary Russell

Questions/Answers/Comments

(P. Egelstaff)

Question:

Some people say that they are more interested in pulse intensity and less interested in pulse shape at (say) 1 Å. In such a case, one might use a hot moderator. Have you done any calculations for this case?

Answer:

No, I have not specifically addressed this issue.

(A. Lee)

Question:

When you remove the decouplers and liners from a moderator, do you cause problems for the pulse shape in the other moderators?

Answer:

No, because the decoupled moderator is, by definition, neutronically isolated (below some cut off energy) from its immediate environment.

(J. M. Rowe)

Question:

You referred to the ability to use coupled moderators with increased intensity, so long as a sharp edge remained. However, I believe that in many cases, the long tail contributes directly to the background. Are you considering this in your optimizations?

(R. Pynn)

Answer:

Of course, one has to optimize the whole system from moderator to spectrometer, and the optimization criterion depends on what one wants to measure. It is different for a measurement of the position and shape of a peak in a neutron spectrum, for example. However, we are sure that a sharp leading edge can give more information in many cases, just as we are sure that an increased background reduces the information content of data. One needs to look at the trade-offs between these two effects by picking a "reasonable" optimization criterion and examining how sharp edges and long tails contribute to this criterion.

A Design Concept for KENS-II Cold Neutron Source

Noboru Watanabe and Michihiro Furusaka
National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305 Japan

Yoshiaki Kiyanagi
Faculty of Engineering, Hokkaido University
Sapporo, 060, Japan

ABSTRACT

KENS-II program as a part of Japanese Hadron Project is briefly described and Figure of Merits for typical experiments with pulsed cold neutrons are discussed in order to obtain a good guide for developing a better pulsed cold neutron source. A coupled liquid hydrogen moderator with a premoderator was thus proposed and its performance is discussed based on the results of extensive optimization experiments. A new target station is proposed which has two target-moderator-reflector assemblies dedicated to coupled cold moderators and decoupled ones, respectively.

I. INTRODUCTION

KENS-II is a next generation pulsed spallation neutron source in Japan for condensed matter research and partly for fundamental physics. The KENS-II was first proposed as a GEMINI project which was aimed at constructing intense pulsed-spallation-neutron and muon facilities with a new high-intensity proton synchrotron (800 MeV, 500 μ A), based on the successful scientific achievement of the KENS-I and Boom (Meson Science

Laboratory, University of Tokyo) facilities at KEK (National Laboratory for High Energy Physics).

Later on the GEMINI project joined with an independent Hadron facility project for nuclear physics in order to be realized as a unit as soon as possible. The Japanese Hadron Project (JHP) was thus proposed to explore various research fields utilizing various kinds of secondary beams: neutron scattering, meson science, nuclear physics with short-lived nuclei beams, and nuclear/elementary particle physics with kaon beams. After significant discussions and compromise between four different research fields we decided, for the first stage, to construct an accelerator complex which consists of a 1GeV H^- linac and a compressor/stretching ring. The layout of JHP is shown in Fig.1.

Fig. 1. Layout of JHP

The proposed site for JHP is located at the forest adjacent to the southern boundary of the present KEK site. The main parameters of the proposed 1 GeV linac is summarized in Table I.

TABLE I
MAIN PARAMETERS OF PROTON LINIAC

Energy	1GeV
Average current	400 μ A
Repetition rate	50Hz
Peak current	20mA
Pulse width	400 μ s
Total length	500m

A new type of cavity structure, Annular-Coupled Structure (ACS), has been developed at KEK which will make it possible to shorten the total length of the 1GeV linac only to 500 meters long. The compressor/stretcher ring delivers a 200 ns pulsed proton beam for the neutron facility (KENS-II) and a short pulsed beam down to 20 ns for the meson science facility as shown in Fig.2.

Fig. 2. Time structure and scheme of proton beam delivery

We aim at realizing the world's best and most attractive pulsed neutron source for neutron beam experiments with a given proton beam intensity from the proposed proton accelerator in JHP, which is not very intense but comparable to those in the existing large scale facilities. The design goal of the proposed source is as follows:

- (1) the world's brightest pulsed cold neutrons;
- (2) bright and narrow pulsed thermal/epithermal neutrons, at least comparable to those at existing intense pulsed neutron sources;
- (3) wider range of neutron spectrum;
- (4) neutron beam lines as many as possible.

In the present paper we report a fundamental design concept for cold neutron sources at KENS-II.

II. FIGURE OF MERIT OF PULSED COLD NEUTRON SOURCE

The definition of Figure of Merit (FOM) for a pulsed cold neutron source depends on the type of experiment. Here we discuss FOM for typical experiments performed with pulsed cold neutrons.

Small Angle Neutron Scattering (SANS)

FOM for SANS will be expressed as

$$\text{FOM} \equiv \bar{J}(\lambda) \text{ BW}, \quad (1)$$

where $\bar{J}(\lambda)$ is the neutron beam intensity of wavelength λ at sample position though beam collimator; BW, the useful band width of cold neutrons. $\bar{J}(\lambda)$ is proportional to 4π -equivalent time-averaged neutron flux $\bar{\phi}(\lambda)$ at the moderator surface. BW is given by

$$\text{BW} = 3.96 \times 10^3 / (fL) \quad (\text{\AA}),$$

where f is the repetition frequency of the source and L the flight path length in meter between source and detector. $\bar{\phi}(\lambda)$ will be expressed to a good approximation by

$$\bar{\phi} \equiv \hat{\phi}_{\lambda}(t) \Delta t_m(\lambda) f, \quad (2)$$

where $\hat{\phi}_{\lambda}(t)$ is the neutron flux at the pulse peak, and $\Delta t_m(\lambda)$ the pulse width.

Thus we obtain

$$\begin{aligned} \text{FOM} &\propto \bar{\phi}(\lambda)/(fL) \\ &= \hat{\phi}_{\lambda}(t)\Delta t_m(\lambda)/L. \end{aligned} \quad (3)$$

This means that FOM is proportional to time integrated neutron flux per pulse, and independent of the repetition frequency f . L shall be the shortest possible flight path length which can realize a required collimation and signal to background ratio.

High Resolution Experiment

Let us consider high resolution experiments like those with LAM-80 at KENS or IRIS at ISIS. In this type of experiment the energy window (same as BW) as well as the energy resolution or the wavelength resolution $R(\lambda)$ become important. FOM will therefore be written as

$$\text{FOM} \equiv \frac{\bar{\phi}(\lambda)}{R(\lambda)} \text{BW}, \quad (4)$$

with

$$R(\lambda) = \frac{\Delta t_m(\lambda)}{t(\lambda)} \propto \frac{\Delta t_m(\lambda)}{L\lambda},$$

where $t(\lambda)$ is time-of-flight between source and sample for neutrons of wavelength λ . Thus we obtain

$$\text{FOM} \propto \frac{\bar{\phi}(\lambda)}{\Delta t_m(\lambda)} \frac{L\lambda}{fL} = \hat{\phi}_\lambda(t)\lambda. \quad (5)$$

This means that FOM is proportional to the peak flux $\phi_\lambda(t)$ and again independent of f . There are other types of experiments for high resolution spectroscopy, which utilize instruments such as MUSICAL, Doppler chopper, Multi detector spin echo machine, etc. FOM for those experiments will be the same as that in eq.(3).

Wavelength Resolution

The wavelength resolution of incident neutrons at sample position L meters from the source is simply given by

$$\begin{aligned} \Delta\lambda/\lambda &= \Delta t_m(\lambda)/t(\lambda) \\ &= \Delta t_m(\lambda)/(250(\mu s) \times L(m)L(\text{\AA})). \end{aligned}$$

Since L will be at least longer than 10m, we assume $L=10\text{m}$. The pulse width in full width at half maximum (FWHM) of neutrons emanating from a proposed moderator (see section III) is about $250\mu s$, almost saturated in the range $\lambda > 4\text{\AA}$. We therefore obtain

$$\Delta\lambda/\lambda \leq 250/(250 \times 10 \lambda(\text{\AA})) = 0.1/\lambda(\text{\AA}).$$

Even for the shortest λ (say $4\text{\AA}$) we obtain $\Delta\lambda/\lambda \leq 0.04$, which will be sufficiently small not only for SANS type experiments but also for CRISP (critical reflection spectrometer) type experiments.

III. FUNDAMENTAL CONCEPT OF KENS-II COLD NEUTRON SOURCE

The results of the preceding section are summarized as follows:

- (1) For the SANS type experiments the higher value of time integrated cold neutron flux per pulse is essential. This requires the development of a new cold neutron moderator system having a high conversion efficiency, with a low-repetition and high-current proton accelerator. Here the conversion efficiency is defined as

time-averaged 4π -equivalent cold neutron flux on a moderator surface per fast neutron emitted from a neutron generating target or a reactor core.

- (2) For high resolution spectroscopy the higher cold neutron flux at pulse peak is essential. This brings an additional requirement both to moderator and accelerator.

All the cold neutron sources presently in operation at pulsed spallation neutron facilities are decoupled moderators for relatively short pulse use. The pulse width of cold neutrons from these moderators is short enough for required wavelength resolution, but time-averaged intensity is not adequate to perform SANS type experiments. Table II compares the conversion efficiency of cold neutrons at spallation neutron facilities with that at ILL. The conversion efficiency at the large-scale pulsed neutron source is especially small compared to that at the high flux reactor. The higher efficiency in present KENS-I' is due to the use of solid methane as moderator material and a larger coupling efficiency between target and moderator which are only possible in a smaller system.

TABLE II
COMPARISON OF CONVERSION EFFICIENCY

<u>Neutron Source</u>	<u>Cold Source</u>	<u>Conversion Efficiency</u>
ILL	Liq. D ₂ in D ₂ O reflector	3×10^{-4}
KENS-I'	Solid CH ₄ decoupled to Be reflector	4.8×10^{-4}
ISIS	Liq. H ₂ decoupled to Be reflector	6×10^{-5}
KENS-II	Liq. H ₂ with premoderator coupled to reflector	$> 4.8 \times 10^{-4}$

As far as neutronics is concerned solid methane is the best moderator material, but cannot be used at intense spallation neutron sources due to serious radiation damage. Liquid hydrogen is at the present time the only one proved material for pulsed cold neutron moderator at an intense spallation source, but the conversion efficiency of a decoupled hydrogen moderator is too low. We studied various moderator system and finally reached to a coupled liquid hydrogen moderator. It has long been believed that this kind of moderator gives very long pulse width compared to a decoupled one, resulting in poor performance overall. In order to realize a high-efficiency pulsed-cold-neutron source which satisfies the requirements mentioned above, eventually the design goal (2) declared in section I, we proposed a cold moderator system which consists of a liquid hydrogen moderator and a premoderator at ambient temperature coupled to the reflector.^[1] A preliminary optimization experiment was carried out using the pulsed neutron source at the electron linac facility at Hokkaido University and the result was already reported at last ICANS.^[2]

Fig. 3. Comparison of relative intensity and energy spectra from four different liquid hydrogen moderators

Energy spectra of time-averaged 4π -equivalent neutron fluxes from four different liquid hydrogen moderators are compared with relative intensities in Fig. 3.

Fig. 4. Ratio of FOM's defined by eq.(3) of the proposed moderator to the reference one

Figure 4 shows the ratio of neutron beam intensity from the proposed coupled hydrogen moderator with 3 cm thick pre-moderator to that from a reference decoupled-liquid-hydrogen-moderator (12 cm wide, 12 cm high, 5 cm thick). This is just the ratio of FOM's given by eq.(3). It was proved that the new moderator brought about six times higher cold-neutron-flux than the reference decoupled-liquid-hydrogen-moderator. Figure 5 shows the time distribution of neutrons at a selected energy (0.82

Fig.5. Time distribution of 0.82 meV neutrons from the proposed moderator (solid square) compared with that from the reference one (open square). Solid curve shows the latter normalized at pulse peak for direct comparison

meV) from the proposed moderator compared with the reference decoupled moderator.

The proposed moderator gives broader pulses than the decoupled one as expected, but the broadening is rather modest and the increase in the peak intensity is unexpectedly high. This means that the larger gain of the coupled moderator is not mainly due to the increase of the pulse width but to the increase in the peak intensity. This feature is very much favorable for a pulsed cold neutron source.

Figure 6 shows the ratio of FOM's defined by eq.(5) of the proposed moderator to the reference one. It turns out that the proposed moderator gives much higher peak height than the reference moderator over a whole wavelength range, especially at a longer wavelength region.

Fig. 6. Ratio of FOM's defined by eq.(5) of the proposed moderator to the reference one

Figure 7 shows the wavelength resolution $\Delta\lambda/\lambda$ per 10 m measured with the proposed moderator.

Fig. 7. Wavelength resolution per $L=10$ m measured with the proposed moderator

It was proved that the performance of the proposed moderator is superior to that of the decoupled-liquid-hydrogen-moderator for both categories of FOM. Furthermore the proposed moderator has advantages in energy deposition, cost for cryogenic system, safety problems, etc. compared to the decoupled one.^[1]

Further optimization experiments were performed to study the effect of the existence of a Cd liner around the beam extracting hole in the reflector, decouplers for different moderators, the spatial importance of the reflector, etc. on the conversion efficiency. We have obtained various important information from these experiments, the detailed results of which will be reported elsewhere. In the preliminary experiment we used a tentative cryostat for liquid hydrogen moderator, which had a large volume above the moderator container and consequently removed considerable parts of the upper premoderator and the upper reflector. We constructed a new cryostat which has a slim neck for minimizing those missing. We have confirmed that the conversion efficiency of the proposed moderator with the new cryostat is already better than that of

the present KENS facility. This means that the efficiency is 8 times better than that of the liquid hydrogen moderator at ISIS.

IV. DESIGN CONCEPT OF KENS-II TARGET STATION

There are increasing demands for utilizing neutron beam in various fields including industrial applications, but the limited number of available neutron beam-lines and the price of the beams prevent the progress of researches. The total number of neutron beam lines or the instruments in a pulsed neutron facility is much smaller than in a high flux reactor. The operation cost for one neutron beam is very expensive, for example in a large scale existing pulsed neutron facility it costs ¥200-300M per year, which is almost same as the construction cost of one expensive neutron spectrometer. Therefore the design goal (4) becomes important to overcome this situation. We altered the scheme of the proton beam injection from the previous "horizontal" to a "vertical" as shown in Fig.8, in order to provide as many neutron-beam-lines as possible in the experimental hole. The proton-beam transport-line in the experimental hall was removed with its massive shield, and a substantial number of extra beam lines took the place as shown in Fig.9. This change will bring a considerable cost saving which will well compensate the cost for extra overhead shield of the target station due to the vertical upward injection, and for the construction of a 90°-bending magnet for primary proton beam.

Fig. 8. Vertical cross section of the KENS-II facility

Fig. 9. Layout of the KENS-II experimental hall

There is another reason why we adopted the "vertical" instead of the "horizontal". As well known there are two different configurations in target-moderator coupling. One is a so-called "wing geometry" which is adopted at present KENS, IPNS and ISIS. Another is a so-called "slab geometry". No spallation neutron facility adopts this configuration because of an inevitable huge fast-neutron background. A new configuration of a so-called "flux-trap moderator geometry" was proposed by Los Alamos group and its higher performance has been demonstrated.^[3] By a computer simulation we carefully compared the neutron beam intensity from a moderator in this configuration with that in the traditional wing geometry, and found that the former gives about 1.5 times higher beam intensity than the latter.^[4] In order to take full advantage of this

configuration the vertical injection is essential. We therefore decided to adopt this target-moderator configuration with a vertical injection scheme.

It turned out from the further optimization experiment on the proposed moderator that the conversion efficiency in this type of moderator decreases significantly with the existence of neutron-absorbing material such as decouplers, liners etc in target-moderator-reflector assembly. This fact suggests that the proposed moderator may not be able to coexist with decoupled moderators in the same target-moderator-reflector assembly. On this problem we are still studying various effects very carefully, but we proposed here a target station which has two target-moderator-reflector assemblies as shown in Fig. 10 with a new scheme of proton-beam delivery as shown in Fig. 11. Every 5 pulses (100 ms) a pair of double pulses is delivered to the target-1 (dedicated for cold neutron source), and other 4 pulses are fed to the target-2 (decoupled moderators for narrow pulses of thermal and epithermal neutrons). The both can be optimized independently.

Fig. 10. Idea of double target-moderator-reflector assemblies

Fig. 11. A new scheme of proton pulse delivery. NC: for cold neutron assembly, NT: for short pulse assembly, M: for meson science

The reduction of repetition rate on the target-1 gives no demerit as discussed with FOM and double pulses give another gain of factor 2. The number of pulses for the target-2 decreases by 20%, but this will be compensated by a gain factor of 1.5 from the "flux-trap moderator geometry". The most important disadvantage of the "flux-trap moderator geometry" is that the total number beam tubes which can be extracted from one moderator is small because the rear side cannot be viewed by any beam tube. The proposed double assembly system can cover the whole angles, which is another important advantage of the proposed scheme.

V. REFERENCES

- [1] N. Watanabe, "A Consideration of Cold Neutron Source for KENS-II" Advances Neutron Sources 1988, Proc. ICANS-X (Los Alamos, Oct. 3-7, 1988), Institute of Physics Conference Series Number 97, Institute of Physics, Bristol and New York, PP. 763-769.

- [2] N. Watanabe, Y. Kiyanagi, K. Inoue, M. Furusaka, S. Ikeda, M. Arai and H. Iwasa, "Preliminary Optimization Experiments of Coupled Liquid Hydrogen Moderator for KENS-II", *ibid*, PP. 787-797.
- [3] G.J. Russell, J.S. Gilmore, H. Robinson, G.L. Legate, A. Bridge, R.J. Sanchez, R.J. Brewton and R. Woods, "LANSCE target system performance", *ibid*, PP. 483-496.
- [4] Y. Kiyanagi et al., in preparation.

A Design Concept for KENS-II Cold Neutron Sources

Noboru Watanabe

Questions/Answers/Comments

(P. Egelstaff)

Question:

Could you tell us how much current will go to the cold neutron target and to the μ -meson facility?

Answer:

If we assume that the total proton beam current from the ring accelerator is 200 μ A, the cold neutron target will receive only 40 μ A. However, this is equivalent to 200 μ A at 50 Hz as mentioned with Figure of Merit. The H^- beam intensity from the Linac is 400 μ A. The beam intensity from the ring accelerator is therefore expected to be increased in the later stage. Furthermore, we would expect to have proton beam directly from the linac on the cold neutron target, which is an extra beam simultaneously accelerated with H^- beam.

On the other hand, the muon facility will receive 80 μ A $((200 \mu\text{A}/2) \times 4/5)$. The shortage will be compensated by a macro-beam sharing, which will just meet the requirement for a continuous beam to the muon facility.

(G. Russell)

Question:

I have found that back-scattering moderators in flux-trap geometry are better than flux-trap moderators in standard geometry at the 20% level.

Answer:

We have also obtained a similar result by computer simulation, although the statistics were very poor.

Session VI

WRAP-UP: WHAT HAVE WE LEARNED?

Chairman

Peter A. Egelstaff

Summary - Reactor Cold Sources

Colin D. West
Oak Ridge National Laboratory
Oak Ridge, TN USA

ABSTRACT

The following view graphs represent a synopsis of presentations concerned with reactor cold sources.

EXISTING REACTOR COLD SOURCES DESCRIBED AT THE WORKSHOP

Facility	Moderator		
	LD ₂	LH ₂	Supercritical H ₂
ORPHEE		*	
ORPHEE		*	
BNL		*	
JRR-3		*	
FRM-1		*	
Julich	*		
KURR	(*) $\xrightarrow{1989}$	(*)	
NIST, D ₂ O ice			
ILL	*		
ILL	*		
Riso			*
Geestacht			*
Berlin	—	—	— *
	3	6	3

- Does anyone have plans/thoughts about supercritical D₂ sources?

PROPOSED REACTOR COLD SOURCES DESCRIBED AT THE WORKSHOP^a

Facility	Moderator		
	LD ₂	LH ₂	Supercritical H ₂
FRM-II	*		
FRM-II	*		
ANS	*		
ANS	*		
NRU	(*) ← (*)		
ORPHEE		*	
MURR		(*) ← (*)	
Cornell			

^a

Excludes changes to the KURR and NIST cold sources already listed on previous viewgraph.

SITUATION WHEN ALL NEW PROPOSALS ARE IN PLACE
(FACILITIES DESCRIBED AT THIS WORKSHOP ONLY)

LD ₂	LH ₂	Supercritical H ₂
KURR	ORPHEE	RISØ
FRM-II	ORPHEE	GEESTACHT
FRM-II	ORPHEE	BERLIN
ILL	BNL	
ILL	JRR-3	
ANS	NIST	
ANS	JULICH	
(NRU) ← → (NRU)		
	(MURR) ← → (MURR)	
(SINQ)		
8 + 1? ^a	7 + 2?	3 + 1?

^a
Plus SINQ.

SOME BROAD LESSONS? (1)

- "Standby Cooling", to Avoid the Need for Reactor Scram/Shutdown on Loss of Moderator Cooling, is Very Important
 - In Many Cases, This is to be Accomplished by Separate Wall Cooling, With a Standby Source of Coolant Flow

- Most Gains in Effectiveness May Come From Careful Design, Optimization, and Construction of the Beam Transport System, but Those are Some New Ideas
 - Reduced Inner Wall Heat Load (Ageron)
 - Coherent Spectrum Shifting (Bauer)
 - $L^{15}N_2$ as a Cool Source or Cold Source Precooler (Hayter)
 - And of Course, More Reactor Flux Always Helps - If the Heat Load can be Handled

SOME BROAD LESSONS? (2)

- Aluminum 6000 Alloys, and Perhaps Magnesium Alloys, are the Structural Material of Choice, Except Perhaps in Special Circumstances
 - Even the Aluminum Embrittles, but we are Desperately Short of Data on Low-Temperature Irradiation Damage Effects
- Design Choices May, Quite Legitimately, Be Driven by Non-Technical Forces
 - E.g., Choice of LH_2 Instead of LD_2 to Avoid Risk of Tritium Venting or Release
- Solid Moderators are not Satisfactory, Even in Only Medium Fluxes, for Extended Periods

SOME BROAD LESSONS? (3)

- Continuous Spallation Sources and Reactor Sources of Neutrons are Similar Enough to Raise Common Problems/Solutions in Cold Source Design
 - Heat Loads are About the Same, at the Same Flux, Although the Distribution Between Gamma and Neutronic Heating is Different

SAFETY (1)

- Safety Issues Are Gaining Visibility (and They Probably Should)
 - Need for Full Documentation of All Safety Issues
 - Written, Effective, Enforced Procedures
 - Documented Operator Training and Certification
 - Safety Review of Design Decisions

- PLAN EARLY for the Entire Safety and Licensing Program

SAFETY (2)

- NASA, With Vast Experience in Hydrogen Safety on Both Large- and Small-Scale Equipment Offered to Help With Information, Procedures, and Reviews

- NASA Offered Some Specific Advice
 - Welded Construction
 - Leak Detection
 - Vacuum Purging
 - Attention to Building Designs, Leak Paths, and Ventilation

- New Thermal Imaging Equipment that can be Useful in Hydrogen Handling is Being Developed

SOME OF THE MAJOR QUESTIONS/PROBLEMS

- Need for Materials Data
- Loss of (Off-site?) Power is a Leading Cause of Cold Source Outages
- Some Ways of Reporting Cold Source Gain Factors are Misleading
 - Need an Agreed, Common Format or Formats?
- There is Much Information "Available" on e.g., Performance Benchmarks, Heat Removal Limits, Post Irradiation Examination (P.I.E.) of Materials
 - But, There is no Bibliography, Much Less a Collection, of all This Information
- Solid Moderator Problems

Summary—Reactor Cold Sources

Colin D. West

Questions/Answers/Comments

(P. Brewster)

Question:

What energy range is to be used for this generic gain figure?

(R. Pynn)

Answer:

I believe that one should have the largest dynamic range possible, say, up to 20 MeV.

(W. Sommer)

Question:

In this community, how does one initiate a program to obtain necessary materials data? What is the consequence of a LD₂ moderator mechanical failure to a reactor system?

Answer:

There is no formal method for a community-wide approach to these problems. However, groups such as this workshop can certainly help to disseminate existing information. Also, if any reactor operator is removing or replacing any high-fluence components, he/she should let the rest of the community know in case anyone would wish to carry out post-irradiation examination (PIE) of the material.

(C. McKibben)

Question:

What is the operating cost (utilities, staff, etc.) associated with a current operating CNS?

Answer:

An answer from the audience suggested that additional operators would be involved but that a single extra technician would be needed.

Comment:

C. West remarked that it was likely, at a high-powered reactor, that one would not wish to add the burden of cold source of section to the operators.

(C. West)

Question:

What do you think the best for the definition for gain factor of reactor cold neutron source?

Answer:

(N. Watanabe) To the question raised by West, I think the ratio of cold neutron flux from a cold source to that from the best beam hole at room temperature moderator is the best definition of a gain factor.

(J. Carpenter) To the question raised by West about gain factors, it seems to me that the concept of a "gain factor" is one of interest specific to a facility, say as a guide to design decisions. I suggest that sources be characterized as well in absolute terms, say the luminous intensity ("beam current") or angular current density at the source surface.

(P. Egelstaff) To the question raised by West about gain factors, there are two definitions of a gain factor that are of interest to us. One is the ratio defined by Mike Rowe, the other is the ratio of flux with the source to the best flux that can be obtained from that beam hole using an ambient temperature moderator.

Cold Moderators at Pulsed Spallation Sources: A Personal View

Roger Pynn,

Los Alamos National Laboratory
Los Alamos, New Mexico U.S.A.

ABSTRACT

When Gary Russell asked me to give a summary talk, I asked myself the natural question: "Why me?" The first answer I gave myself was the obvious one: "I'm being victimized." But after a little thought, I decided that the real reason is that I know little or nothing about the subject of pulsed-source moderators. And that can be a tremendous advantage. When Maier-Leibnitz built the ILL, he came first to the U.S. and to Canada where there were several prominent neutron scattering centers. He asked what instruments he should build. The reply was unanimous: "First you build some three-axis machines to form the base program and then you see what else you can think of." Maier-Leibnitz's reply was equally characteristic: "Thank you very much...there will be no three-axis spectrometers at my institute." He wasn't quite right - there was one at the beginning. But the point is that, instead of following conventional wisdom, Maier-Leibnitz hired a bunch of young scientists who didn't know as much about neutron scattering as their colleagues on the American continent and who therefore did not know what was "impossible." So, they built the impossible - a cold source integrated into the reactor, several hundred meters of guides, a 40-meter SANS machine, a back-scattering spectrometer, a hedgehog - the whole works. And they changed the face of neutron scattering forever. I am going to adopt the same philosophy - because I know very little about cold moderators at spallation sources, I don't know what is possible or what is stupid. So I'm going to try to make some outrageous comments to stimulate Peter Egelstaff's discussion session. I make these remarks, not as Director of LANSCE, but as a research scientist looking well beyond his area of expertise.

The first outrageous statement I want to make is that thermal equilibrium is boring and there is therefore not much more to do in cold-source design at reactors. You have to understand the spirit in which this remark is made. I do not mean to belittle the engineering problems which cold source designers face, especially at high-flux reactor sources. But I am, or was, a research scientist, not an engineer; and for this reason I am more fascinated by things I do not understand than by engineering detail. In this context, the non-equilibrium situation which pertains to moderators at spallation sources offers a far richer variety of properties and opportunities than is available at reactors.

Let's take the whole question of optimization which was raised at this meeting both by Gunther Bauer and Noboru Watanabe. What are we really trying to optimize? I claim that we want to optimize the information content of neutron scattering data, and that this is the real *raison d'être* for cold sources. But how do we decide how much information there is in such data? One way, which we have been investigating at LANSCE, is to use a method like maximum entropy to define the information content of data. The idea is to imagine a "typical" neutron scattering law or spectrum, to convolve this with the resolution function of a spectrometer (including contributions from the neutron source), to add Poisson noise and background, and then to use the maximum entropy method to see how well one can retrieve the original neutron scattering law. This analysis tells you whether the instrumental resolution function is preserving information in the measured neutron spectrum, even in cases where the data bear little or no resemblance to the scattering law. But if this sort of calculation were the only tool we had, optimization of instrument and source design would be a tedious process. We would have to simulate an extensive set of different spectrometers and sources, and make a huge table of machine parameters versus information content of the data obtained with these machines. From this we could, at least in principle, decide the optimum instrument parameters.

Unfortunately, even if we could use the maximum entropy method in this way for a vast array of spectrometers and sources, we would quickly discover that the optimum instrument parameters depend on the experiment we are doing, that is on the neutron scattering law we are trying to measure. For example, the optimum instrumental parameters are quite different for an experiment which is trying to locate a peak in a spectrum and for one which is trying to measure the peak's intensity. In one case, good resolution is needed, while in the other, total neutron intensity is most important. The bottom line is that there is no single optimization criterion and this makes it very difficult to decide what an optimized cold moderator should look like at a pulsed spallation source.

We^[1] have tried to address this issue by proposing a generic figure of merit which can be used for optimization calculations and which takes account of both spectrometer resolution, source intensity, and background in an approximate manner. Our compromise figure of merit for deducing structure with a resolution Δx in a measured spectrum (x is the abscissa against which the measured intensity is plotted) is:

$$\text{FOM}(\Delta x) = \frac{\phi |f(k)|^2}{f(0) [1 + N_b/N_s]} ; \quad \text{with } k = 2\pi/\Delta x$$

where $f(k)$ is the value of the Fourier transform of the normalized resolution function at 'wave number' k , f is the peak count rate per unit spectral length (x), N_s is the total number of neutrons in the signal and N_b is the total number of background neutrons. The idea is that one can decide which source or spectrometer parameters are best by maximizing the FOM given in the above equation, even though this figure of merit cannot be completely accurate for all types of measurement. We have found that this FOM is in qualitative agreement with the results we get if we use maximum entropy to define the amount of information in the data. In particular, we have found that neutron pulses which have steep leading edges (in time) often give a much larger FOM than symmetric pulses of the same total width.

This observation leads to the idea that it may be possible to optimize cold moderators and neutron spectrometers at spallation sources in a different way than has been done in the past. Perhaps one can maintain the sharp leading edge and gain some intensity at the same time, thereby improving the FOM and increasing the information content of neutron scattering data. In addition, it may be desirable to match other components of spectrometer resolution functions to the leading edge of the neutron pulse rather than to the total pulse-width. Of course, people at this conference and elsewhere constantly remind me that the rise time of a pulse from a coupled moderator may not be as sharp as that for a decoupled moderator, and that the long tail of the pulse in the coupled case can contribute an effective background. To which I can only reply, once again, that all I care about is the information content of the data, as given either by the FOM or by a maximum entropy simulation. Both methods include explicitly all of the features of the moderated pulse, so if the tails of the pulses are a problem, for example, they will result in a decrease of the information content and of the FOM.

Mike Rowe told us yesterday that informed intuition is available to help designers of cold sources at reactors. This is a manifestation of two things: the thermal equilibrium of the sources and long years of experience with such sources. At pulsed spallation sources, our intuition is limited. Monte-Carlo calculations reproduce quite well the measurements made with existing moderators, but it is not clear to me that we really learn anything fundamental from these calculations. They are just a slightly cheaper and quicker way of doing experiments; they use a Cray instead of liquid hydrogen to provide a data base which helps our intuition but not necessarily our basic understanding.

To put the Monte-Carlo calculations in perspective, I like to use the analogy of the design of a high-performance mechanical component. The initial, conceptual design of such a component is usually based on experience or intuition. The next step involves calculations with a simplified model which gets the gross features right but doesn't include all the details. Finally, before fabrication, a finite-element analysis may be carried out to optimize design parameters. In the field of moderator design at pulsed spallation sources, Monte-Carlo calculations provide the data base needed to fuel the initial intuitive part of the design. They are also the finely honed tool which is analogous to finite-element analysis. What is missing is the intermediate step - the relatively simple calculation which includes the essential physics. Without the deeper understanding which such calculations provide, it is not clear to me that we will be able to exploit fully the richness which spallation source design can offer. What we need, in addition to the Monte-Carlo codes, is computer-aided intuition - a program run on a PC which can answer simple "what if" questions. Of course, this is very hard to realize because material properties and geometry are inextricably entwined with the performance of pulsed source moderators. Perhaps the approach used by Varley Sears in the small-moderator limit could be of some help in this area.

We know a lot less about the design of cold moderators at pulsed spallation sources than we do about the same problem at reactors. We do know, as Jack Carpenter explained to us, that cold sources are needed at spallation sources to extend the slowing down region; we know that cold moderators provide higher proton densities; and we know that they increase the fluxes of long wavelength neutrons. Not so long ago, many people believed that there would not be sufficient long-wavelength neutrons to be useful at spallation sources. This has turned out to be untrue, especially here at LANSCE where our repetition rate is only 20 Hz. On our reflectometer, for example, we use neutrons all the way out to 32 Å. There aren't many of them to be sure, but they are useful.

We also know that cold sources at LANSCE (and perhaps at ISIS) can now produce a peak neutron flux which is higher than the average flux at advanced reactors like the HFR in Grenoble. This has important consequences. For example, our small angle scattering spectrometer can outperform the D-11 spectrometer at ILL over the wavevector range $0.004 \text{ \AA}^{-1} < q < 0.5 \text{ \AA}^{-1}$. Of course, at smaller values of q , D-11 wins, so the pulsed sources and reactors should really be regarded as complementary, not as alternatives. But, the point I want to make is that cold sources at spallation sources have come a long way in a short time. And we know that richness of the "pre-equilibrium" situation which prevails in pulsed source moderators will allow us to go on improving.

Gary Russell already told us about some improvements he could envisage making to existing cold moderators at pulsed sources. Back scattering moderators appear to buy a few tens of percent and composite moderators - liquid hydrogen with a water pre-moderator, for example - promise a further 50% or so. I would like to suggest that much more work is needed on composite moderators - both those which use homogeneous mixtures of materials and those in which different materials are spatially separated. There appears to be no reason why we can't take advantage of the high proton density of one material and the abundant low-energy modes in another. A stupid idea I'd like to throw out is that of having a moderator with several chambers which can be filled with different liquids. These liquids could be pure moderators or might contain poisons. Perhaps we could even tune our moderators to give different pulse shapes and intensities if the optimization procedures described above told us that this is desirable.

Finally, I'd like to come back to two points made by Gunther Bauer which I believe to be absolutely crucial. A cold moderator - be it at a reactor or at a spallation source - simply effects an incoherent phase space transformation on a neutron gas. At spallation sources we have more opportunity to tailor the results of this transformation than one does at a steady-state source. Nevertheless, the transformation remains incoherent and unoptimized. We need to pay much more attention to coherent transformations, where neutrons are moved to specific volumes of phase space and used in an optimum fashion. As the SNQ instrument designers showed, there are potential factors of ten to be gained by applying imagination in this area. Lastly, we should remember that only those useful neutrons which impinge on a sample count: so careful beam transport becomes an important issue at both reactors and spallation sources. The job of the cold source designer does not finish when neutrons leave the moderator, only when those neutrons reach a spectrometer.

Acknowledgements

I want to thank Gary Russell and Colin West for organizing this very successful and stimulating meeting.

References

1. D. S. Sivia, R. N. Silver and R. Pynn., Nucl. Instrum. Methods, A287, 538 (1990).

Some Concluding Remarks About Cold Moderator Development

John M. Carpenter
Argonne National Laboratory
Argonne, IL 60439

Abstract

This is the transcription of remarks made at the conclusion of the Workshop, including some questions that emerged, some suggestions that arose and some general observations.

I. Scattering Functions

We need inelastic scattering data for cryogenic moderator materials to enable calculations of moderator performance and thus to support informed design decisions and interpretation of measurements. Ideally, the data would be in the form of the full scattering law $S(Q, \omega)$, represented in some format appropriate for input to Monte Carlo and other neutron transport codes. The functions must accurately represent the temperature dependence of the scattering, and account properly for the possibility of thermodynamic non-equilibrium of the medium (as for example in cold ortho-para H₂.) Of course descriptions of the scattering from some candidate moderator materials already exist at some level of approximation. These need to be checked and improved (the liquid state effects are difficult to describe).

Cryogenic moderator performance depends sensitively on the internal molecular vibrational motions, the free-or-nearly-free molecular rotational motions, and on the center of mass motions.

Broadly speaking these are respectively in the ranges of tens to hundreds of millivolts, few millivolts and few-to-submillivolts. Measurements performed to support the development of scattering laws require different instruments to address these different energy transfer ranges. In a real sense, the effort is one of "bootstrapping", using existing neutron facilities to provide data needed to improve the neutron sources, as suggested by Figure 1. Peter Egelstaff showed us how to do this more than thirty years ago! It should be easy now, using existing instruments for example on the pulsed sources, chopper spectrometers for the high energy transfer ranges and crystal analyzer instruments for the low energy transfer ranges. There may be a problem convincing scientific program committees that these experiments are worthwhile, in that their responsibility is to deal with research applications of the instruments, rather than development applications such as the present suggestion.

Figure 1. Using existing neutron facilities to provide data to improve neutron facilities.

II. Cold Moderator Materials

Both the structural material and the moderating material must be considered in cold moderator design. Table I below illustrates the matrix of choices. The x's represent implementations in at least one installation. Choice of structural material represents a compromise among properties of neutron attenuation by absorption and scattering, strength at operating temperature, radiation damage tolerance, and fabricability. The choice of structural and moderating materials is not

independent (therefore the matrix), although the nature of interactions in the choices is beyond my capability to state here.

Table I
Moderator and Structural Materials
for Cold Moderators

Mod'r → Struct'r ↓	L-H ₂	L-D ₂	L-(H ₂ +D ₂)	S-D ₂ O	L-CH ₄	S-CH ₄	L-H ₂ +TiH ₂
Al	x	x			x	x	
Mg				x			
Steel	x						
Zr							
:							
:							

Rutherford Laboratory uses supercritical hydrogen (15 atmospheres absolute pressure) in a steel container. The entry for mixed H₂ and D₂ is intended to remind designers that a carefully-optimized mixture may be better than either one alone, depending on application. The same idea applies to CH₄, say employing CH_{4-x}D_x (but see below some comments on the composition of irradiated mixtures). Far-out possibilities like heterogeneous mixtures of TiH₂ with liquid H₂ seem to offer the advantages of high proton density with the good low temperature thermalization properties of Hydrogen. These prospects need to be evaluated. John Hayter once suggested using isotopic ¹⁵N₂, to eliminate the large capture in natural Nitrogen and capitalize on the small rotational level spacing of N₂. Inhomogeneous mixtures of solid CH₄ in liquid Hydrogen have been discussed to avoid the problems of "burping" in irradiated solid methane. An unresolved problem is to determine whether, to what extent and why ortho Hydrogen is advantageous over para Hydrogen. Scattering kernels need to be developed to support these assessments.

Steel is substantially stronger and easier to weld than Al or Mg, but has higher absorption and scattering cross sections. Zirconium (or Zircaloy) is also stronger and easier to weld than Aluminum or Magnesium, but like Iron has a substantially larger coherent scattering cross section. The Bragg scattering from moderator containers should probably not be greatly feared because the scattering should have little effect in an isotropic neutron field such as exists near the source.--this assertion needs to be verified by calculation or experiment.

III. Radiation Mixing of Chemical Composition

Questions arose several times during our discussions, which should at least be contemplated in the light of the realization that the high radiation fields in operating moderators can cause important configurational changes in the material which may alter their neutronic properties. We are aware of the aggradation of light hydrocarbons into H_2 and heavier hydrocarbons, for example. These are inferior moderators and collect to form voids and to clog flowing systems. Additionally, radiolytic decomposition and subsequent recombination will lead to reversion of para Hydrogen to normal Hydrogen--is this a contributing factor in the mystery of why supposedly ortho Hydrogen and para Hydrogen seem to differ little in their moderating properties?. Mixtures of H_2 and D_2 will reform to an equilibrium mixture of H_2 , D_2 and HD . Isotopically substituted methane, for example CH_3D , will reform into an equilibrium mixture of CH_xD_{4-x} .

Figure 2 illustrates the point in the case of H_2 and D_2 mixtures.

Figure 2. Radiation-induced reformation of an H_2 - D_2 mixture.

Assuming that the binding energies of all species are identical, the equilibrium concentrations of the chemical species will reach a statistically determined equilibrium.

The relative numbers of the different atomic species are

$$p_H = N_H / (N_H + N_D) = N_{H_2}^0 / (N_{H_2}^0 + N_{D_2}^0)$$

$$p_D = N_D / (N_H + N_D) = N_{D_2}^0 / (N_{H_2}^0 + N_{D_2}^0)$$

where

$$N_H^0 = 2N_{H_2}^0, N_D^0 = 2N_{D_2}^0 \text{ and } N_{HD}^0 = 0$$

are the initial numbers.

In equilibrium the relative numbers of molecular species are

$$P_{H_2} = p_H^2, P_{D_2} = p_D^2, \text{ and } P_{HD} = 2p_H p_D.$$

Here I have not treated the dynamics of the reformation, which takes place gradually according to the rates of radiolytic decomposition and recombination.

The same reasoning applies to other situations. For example for an initial charge of $(1 - x)CH_4 + xCH_3D$ with

$$p_H = 1 - x/4, p_D = x/4,$$

the equilibrium relative numbers of molecular species are

$$P_{CH_4} = p_H^4, P_{CH_3D} = 4p_H^3 p_D, P_{CH_2D_2} = 6p_H^2 p_D^2,$$

$$P_{CHD_3} = 4p_H p_D^3 \text{ and } P_{CD_4} = p_D^4.$$

The (questionable) assumption here is that the rates of radiolysis that affect reformation from the CH_4 - CH_3D mix predominate over the rates that produce the heavier hydrocarbons. In this case however, radiolysis generates a mix of other, heavier hydrocarbons, C_2H_6 , C_3H_8 , . . . and their isotopically substituted analogs, which I have ignored. The final equilibrium probably consists of Carbon and H_2 . The full dynamics involves a complicated transition which depends on rates of radiolysis which are unknown and on details of the system.

In Hydrogen at low temperatures, radiation can be expected to reform the low temperature, predominantly para hydrogen into a more nearly normal hydrogen mixture. The spontaneous conversion of ortho to para Hydrogen is usually described (ignoring the backward reaction as is appropriate at low temperatures)

With the constraint on the concentrations

$$C_{\text{ortho}} + C_{\text{para}} = 1$$

the kinetic equation is

$$\frac{dC_{\text{ortho}}}{dt} = -KC_{\text{ortho}}^2,$$

$$C_{\text{ortho}}(t) = \frac{C_{\text{ortho}}(0)}{1 + KtC_{\text{ortho}}(0)}$$

and

is the solution. When radiation decomposes either species presumably the recombination takes place at random, producing normal Hydrogen (3 ortho:1 para)

so that the kinetic equations (ignoring the back reaction, and catalytic effects which can be important) become

$$\frac{dC_{\text{ortho}}}{dt} = -KC_{\text{ortho}}^2 - \frac{1}{4}RC_{\text{ortho}} + \frac{3}{4}RC_{\text{para}}$$

$$\frac{dC_{\text{para}}}{dt} = KC_{\text{ortho}}^2 + \frac{1}{4}RC_{\text{ortho}} - \frac{3}{4}RC_{\text{para}}$$

where R is the rate of destructive collisions per molecule. These equations can be reduced, using the condition $C_{\text{ortho}} + C_{\text{para}} = 1$, to an easily-solvable single Ricatti equation similar to the equation for C_{ortho} . Some estimates based on realistic assumptions show that the effect of radiolysis and random recombination can alter the equilibrium ortho-para ratio so that the equilibrium result is nearly normal Hydrogen, even at low temperature and even at the low radiation levels characteristic of pulsed sources. Perhaps this is the basis for an explanation of why normal and what is presumed to be para Hydrogen behave similarly as moderators. It is important to recognize that the "equilibrium" here is not thermodynamic equilibrium, so the scattering function does not have the detailed balance property.

IV. Comparison of Some Pulsed Moderator Spectra

Figure 3 illustrates the intensity advantage of cold sources for long wavelength neutrons. The figure shows the wavelength spectra as measured with a " $1/v$ " detector in the pulsed beams of IPNS, so that the counting rate distribution is proportional to $\lambda\phi(\lambda)$. The spectra are arbitrarily normalized to 1.0 at $E = 1.0$ eV (wavelength = $.28 \text{ \AA}$), which is approximately appropriate (we cannot measure absolute spectra).

Figure 3. Comparison of flux spectra for 350 K polyethylene, 105 K liquid methane and 20 K solid methane.

Three spectra are shown, one for ambient temperature (about 350 K) polyethylene poisoned with .5 mm Cd 25. mm below the viewed surface, one for a 105 K liquid methane moderator poisoned 17 mm below the surface and one for a grooved, 20 K solid methane moderator. Comparing the polyethylene and liquid methane spectra in the range of the Maxwellian peak, two effects are visible: the peak of the Maxwellian is shifted in wavelength as expected according to the square root of the

temperature ratio; the more severe poisoning of the liquid methane moderator leads to a significant loss of the integrated intensity in the Maxwellian, even so the flux of long wavelength neutrons from the liquid methane is about 3x higher. Comparing the solid methane with the polyethylene reveals two effects: the 20 K moderator shifts the Maxwellian to still longer wavelengths, and the grooved, unpoisoned moderator produces a larger Maxwellian flux relative to the epithermal flux, the result is that the flux of long wavelength neutrons is more than 300 x greater!

The discontinuity at $4.67\text{\AA}$ is due the 111 Bragg edge in Aluminum, and is one of several such features caused by scattering of neutrons from the beam by Aluminum structure in the beam; these serve as markers of the wavelength scale.

V. Some New Ideas to Explore

A number of new ideas for improved moderators arose during the conference. Here I focus on the ones that relate to the moderation process, including some of those mentioned in previous sections of this report. Some of these might best be evaluated by tests, others by calculation.

Hydrogen Mixtures

H₂ and D₂ might be advantageously mixed in liquid hydrogen moderators (H₂O and D₂O in cold ice moderators) because of their significantly different migration and diffusion lengths, and thus matched to the different requirements of cold sources of different sizes. In these instances, the effects of radiation on mixing the chemical species needs to be recognized, as discussed above.

Premoderators and Shields

Surrounding the principal cold source with, say, H₂O and/or Lead, can reduce the thermalization and gamma ray heat loads in the cold material and the container, and thus reduce the refrigeration requirements and alleviate problems in the design of the container. (Radiogenic Lead, lower in ²⁰⁷Pb than common Pb may be useful to reduce the flux depression in reactor cold sources.)

Composite Reflectors

In pulsed sources, as Gary Russell's calculation first showed, a composite reflector of Beryllium outside of which is Nickel, may be able to provide some tens of percents intensity advantage over simple Be or Ni reflectors. This idea is ready for test.

Exotic Moderator Materials

John Hayter has explored the possible use of $^{15}\text{N}_2$ as moderator, capitalizing on the fact that it has a lower capture cross section than $^{14}\text{N}_2$. Although Nitrogen is more massive than Hydrogen, and therefore is inferior for slowing down neutrons from high energies, this feature leads to lower rotational level spacings and more efficient thermalization to low temperatures. $^{15}\text{N}_2$ might be useful as a premoderator surrounding conventional cold moderators, since it is easy to cool to 77 K.

Deuterated Methanes

One of the reasons that CH_4 is a superior moderator is the presence of a high density of internal rotational modes, which are nearly free even in the low temperature solid. In spite of the sacrifice in the proton density, CH_3D or other deuterated methanes might provide even better moderation to the lowest energies. The idea rests on the observation that in the coldest methane moderators neutrons with energies below about 1. meV (12 K) can lose more energy only by exciting center-of-mass translational modes. Figure 4 illustrates how the rotational band structure of deuterated methanes admits lower energy transitions than CH_4 . This is partly due to the lowered symmetry of the substituted molecules and partly due to the higher moments of inertia about the unique axes in the substituted species. Monte Carlo calculations will be impractical until scattering kernels are developed for the nonspherical deuterated molecules, but tests could be done if the materials were available. The effects of radiation reformation of the mixture need to be kept in mind in practical applications.

Figure 4. Rotational energy levels of methane and deuterated methanes^(1,2).

Mixed Moderator Materials

Peter Egelstaff has suggested that Kr be mixed with CH₄ to "free up" the molecular rotations in solid methane. This suggestion might initially be evaluated by molecular dynamics calculations.

Andrew Taylor and I once discussed the possible advantages of mixed metal hydride (e.g. TiH₂) with liquid Hydrogen, to gain the advantages of high average proton density with low temperatures. The same idea might be applied to CH₄. These ideas might be evaluated by Monte Carlo calculations.

Juergen Eckert suggested use of Hydrogen or hydrocarbons in zeolites. The idea, I think, is that the host might advantageously modify the motions of the principal scatterer. Such schemes might be evaluated by molecular dynamics calculations.

Circulating suspensions of solid methane in (for example) liquid Hydrogen or small spheres or thin plates of methane in liquid Hydrogen would eliminate or go far in diminishing the problems of "burping" of irradiated, cold solid methane. Such schemes present yet unsolved engineering problems, and would need neutronic evaluation.

About Tests

There are only a few facilities where tests can be made. For pulsed moderators, The Los Alamos "Blue Room" and the Hokkaido University Linac (Sapporo) provide the needed combination of modest intensity and accessible environment. Pulsed source tests are simple and revealing, even for materials intended for steady source applications, but then the connection between the tests and the applications has to be made through calculations.

Realistic reactor tests of full scale cold sources are difficult, although some kinds of tests might be made merely by substituting materials in existing sources.

VI. Conclusions

This meeting, the first addressing this subject, has been very productive in revealing progress and pointing up problems and areas of opportunity. There seemed to be general agreement that another similar meeting should be convened in two or three years.

VII. Acknowledgement

This work was performed under the auspices of the U. S. Department of Energy, Division of Materials Sciences, Office of Basic Energy Sciences, under Contract W-31-109-Eng-38.

VIII. References

1. E. B. Wilson, Jr., J. C. Decius and P. C. Cross, "Molecular Vibrations", McGraw-Hill, New York, 1955, p. 361 ff.
2. G. W. King, R. M. Hainer, and P. C. Cross, J. Chem. Phys. **11** (1943) 27-42.

Poster Session

1

1

1

1

1

1

1

Cold Neutron Source for the present Munich Reactor

E. Krähling, J. Reschenhofer, W. Gläser

Fakultät für Physik E21 der Technischen Universität München
D-8046 Garching, BRD

ABSTRACT

In the cold neutron source for the Munich Reactor (FRM) the following special design and process-engineering features are realized: subcooled H_2 liquid for a minimum of bubbles in the moderator, rectangular-parallelepiped shaped moderator chamber for optimal illumination of neutron guides, thin walls for high cold neutron transmission and a special flange construction with integrated He-barrier in front of the beamtube, suitable for exchange of the moderator chamber without disassembly of the neutron guide system. With completed cold source components an out-of-pile test run of the H_2 -thermosyphon circuit was performed in order to verify the calculated data and expected behavior.

I. INTRODUCTION

The increasing interest in the research with cold and ultra cold neutrons lead to the conclusion of a cold neutron source installation at the FRM

II. DESCRIPTION OF THE FACILITY.

For the installation of the cold neutron source the rectangular shaped QR beam tube with 3 also rectangular neutron guides with large cross-sections (ca. 230 x 30 mm) was chosen. Therefore a rectangular-parallelepiped shaped moderator chamber had to be constructed for optimal illumination of the neutron guides. Figure 1 shows the total in-pile-set up of the cold neutron source. For more details of the moderator chamber see figure 2.

A special flange construction with an integrated He-barrier (see fig. 1) in a distance of 600 mm from the edge of the reactor core is necessary for the installation of the divided beam tube with regard to the design principle. In addition this construction makes it possible to exchange the front part of the beam tube with its internal cold neutron source components without disassembly of the neutron guide system. The position of the neutron guides as a consequence of the flange design does not reduce their optimal illumination. In order to get a low absorption of cold and ultra cold neutrons in the beam tube, thin walled structure parts had to be developed. The total thickness of walls for neutron transmission could be minimized to 4 mm Al Mg3 material.

The nuclear heat input into the moderator and into the thermal insulated parts of the cold neutron source near the reactor core is removed completely by the H₂-thermosyphon circuit (natural convective circulation). The thermosyphon circuit consists of the moderator chamber, the He cooled He/H₂ heat exchanger located out of the reactor radiation field 2.5 m above the reactor core and two transferpipes of a 26 mm diameter connecting these components. The circulating subcooled liquid hydrogen removes the heat by warming up the liquid from 15 K to 24 K without boiling. The cooling system (He-refrigerator and thermosyphon circuit) is designed for a nominal heat input of 700 W corresponding to a He-refrigerator throughput of 460 m³/h (15°C, 1 bar). With regard to low costs at now only 3 He compressors (3 · 115 m³/h) are installed hoping to

Fig.1 Inpile construction of the FRM Cold Neutron Source

satisfy the expected heat input of 525 W. In an out-of-pile test (see Chap. IV) with the operation of 3 compressors a cold power of 625 W has been determined, which seems to be sufficient.

The cold part of the facility is connected by a 80 m long transferpipe having a diameter of 72 mm with the H₂-buffer located outside the reactor building.

In table I the basic design and process-engineering data of the cold neutron source are listed. For the conception and calculations data from references [1] to [8] were used.

The temperature control system keeps the He_{inlet} temperature T_3 of the He/H₂ heat exchanger (see fig. 1) on a constant value of 14.5 ± 0.2 K. The excess cold power is heated in the He back flowing pipe between He/H₂ heat exchanger and the He-refrigerator, in this way the He refrigerator is operating under constant heat load conditions.

In cases when the He refrigerator is not ready for use 4 MW standard reactor power operation is nevertheless possible. For the protection of the internal cold parts of the beam tube near the reactor core against superheating ($T > 150^\circ\text{C}$) the usually highly evacuated beam tube is filled with He gas. Under these conditions the nuclear heat from the internal parts is transferred by a 1 mm He gas gap between the internal parts and the inner surface of the beam tube to the pool water. An additional standby cooling system is not required. Considering out-of-pile test data even the cooling down of the cold neutron source from roomtemperature seems to be possible during 4 MW reactor operation. Therefore the vacuum space containing the thermosyphon parts is divided into two separately pumped sections in a short distance below the He/H₂ heat exchanger.

Besides a monitoring system a lot of design and process-engineering safety precautions are realized. These are mainly:

Within buildings the H₂-system is covered by an inertgas system with a low overpressure against the atmosphere. For this purpose He is used as

an inertgas for the cold part as well as N_2 for the warm part of the H_2 - system. Within the reactor-pool the poolwater forms a "barrier" against air input into the vacuum space containing the cold parts of the H_2 - system. The vacuum tube surrounding the two cold transferpipes in the reactorpool is designed in a way, that in case of leakage its free cross-section cannot be plugged up by H_2O -ice (see fig 3).

Fig. 2 Moderator chamber

Out of buildings overpressure of the H_2 -system avoids an air input. The transferpipe to the H_2 -buffer is generally welded. The hydrogenhouse with its H_2 -filling and discharging systems is planned and furnished to be in accordance to the German safety regulations for rooms with explosible H_2 -atmosphere.

An integrated "electronic checklist" controls the proper preparation of the H_2 -system before the inletvalve for H_2 -filling can be opened. In cases of safety relevant incidents the hydrogen (liquid or gaseous) is completely blown out of the H_2 -system by He-gas.

Fig. 3 Vakuumpipe cross - section
with H_2 -transferpipes

III. DEVELOPMENT OF SPECIAL STRUCTURE AND PROCESS-ENGINEERING COMPONENTS

With regard to later installation of the cold neutron source into the reactor pool, to the optimal neutron physical using and last not least to safety aspects special structure and process-engineering components have been developed. As important examples the moderator chamber, the front part of the QR beam tube with its He-barrier flange construction (see fig.4), the He/H₂ heat exchanger and a temperature measuring unit for Pt-resistance thermometer, are mentioned.

The requirements on optimal illumination of the neutron guides and in particular on a very low absorption of ultra-cold neutrons lead - under consideration of material strength and manufacturing aspects - to the moderator chamber design as it is shown in figure 2. Besides strength aspects the supporting rods perform two further functions: at first a good and defined heat transfer also in case of gas flow in the thermosyphon circuit and secondly a good heat conduction from the back - to the front side of the moderator chamber in case of standby cooling. Many welding, manufacturing and pressure tests have been performed before the final solution was found - manufacturing the internal contours by electro-erosion technique and WIG-welding the two parts in the middle of the chamber. For the AlMg3 moderator chamber it could be shown that it withstands the foreseen testing pressure of 8 bars. The total cost for manufacturing the last type design were about 10 000 DM.

For the design of the front part of the QR beam tube the installation 1 m below the residual poolwater level (required for radiation protection) and the 1 mm gap between the internal cold neutron source components and the internal surface of the beam tube (required for heat transfer in case of standby cooling) had to be considered. The first requirement lead to a "closed" construction, so that the manufacturing had to be realized step by step between welding and installation of cold components in order to avoid a detraction of the accurate in electroerosion technique performed internal contours of the beam tube.

Fig.4 H₂/He-heat exchanger

Fig.5 He barrier of the CNS beamtube

The callots of the He-barrier flange construction have been manufactured by using water pressure for the deformation of the 1 mm walled flat closing the free cross-section. Bursting pressure tests have shown that these callots withstand a pressure load up to 25 - 30 bar.

The design of the He/H₂ heat exchanger was determined by the following four requirements: a.) low volume on the H₂-side of about 2 l, b.) low H₂ - pressure drop in coincidence with a good heat transfer with respect to the very low hydrostatic pressure acting as driving force (ca. 2 mbar = 200 Pa), c.) absolute prevention of H₂-input into the He-refrigerator system because of safety reasons and d.) a mass of not more than ca 100 kg with regard to the cooling down time. These aspects lead to the construction as it is shown in figure 5. The first and second requirement were realized by 0.5 mm chanal gaps for the H₂-subcooling which lead to a reasonable size. (15 plates of 700 x 275 mm² and a breath of 290 mm). The third requirement was realized by rectangular copper tubes between the exchanging surfaces, which are in connection with the vacuum space containing the He/H₂ heat exchanger. The high thermal conductivity of copper especially in the temperature range of about 20 K does not detract the heat transfer significantly. The fourth requirement could be fulfilled with a total heat exchanger mass of 115 kg.

Because of the lack of a measuring unit suitable for the simultaneous monitoring of 14 temperatures the needed unit was developed in collaboration with an electronic company. Spectral pure Pt-resistance thermometers were chosen as temperature sensors in order to cover the range from 13 to 500 K with a single type of sensors. Its main features are: $\pm 0,2$ K absolute temperature accuracy at 13 K and possible use of sensors with different specific data. In the range from 13 to 30 K an agreement of ± 0.15 K could be verified as compared to a H_2 vapor pressure thermometer.

IV OUT- OF-PILE TEST RESULTS

With completed cold neutron source components an out-of-pile test was set up to study the standard operation and the incident behavior of the facility. The reactor heat input was simulated by an electrical heater fixed on the outer surface of the moderator chamber. Two types of runs were carried out, one with a He-refrigerator throughput of $340 \text{ m}^3/\text{h}$ (1 bar, 15°C) corresponding to a nominal cold power of 525 W and the other one of $460 \text{ m}^3/\text{h}$ for 700 W cooling power respectively as a planing reserve. (The 700 W run was realized using a compressor of another He-refrigerator supplying a higher capacity than the 3 compressors installed for the cold neutron source). The results of the out-of-pile tests are:

The cooling down time of the complete facility with a final He-troughput of $340 \text{ m}^3/\text{h}$ was 7 1/2 hours. Ca 2 1/4 hours after starting the He-refrigerator the H_2 -thermosyphon circuit began working when the temperature decrease at the moderator chamber could be observed. At this time the temperatures at the He/ H_2 heat exchanger (see fig. 1) were:

H_2 - side: $T_1 = 274 \text{ K}$; $T_2 = 188 \text{ K}$

He - side: $T_3 = 180 \text{ K}$; $T_4 = 254 \text{ K}$

3 1/4 hours later the hydrogen condensation began at a temperature of $T_2 = 26.5 \text{ K}$ and 4.3 bar corresponding vapor pressure in the H_2 -system. 35 minutes later the begin of H_2 -subcooling could be observed by a temperature at T_2 measuring point dropping below the value as determined via vapor pressure curve.

Fig. 6 a

Temperatures at the He/H₂ heat exchanger

H₂ - side
T₁ = Inlet, T₂ = Outlet

Fig.6b

He-side
T₃ = Inlet, T₄ = Outlet

Temperatures at cold end of He-refrigerator

T₅ = Outlet, T₆ = Inlet

The figures 6a and 6b show the temperatures at the He/H₂ heat exchanger and at the cold end of the He-refrigerator as a function of the moderator heat input for different values of He-throughput (see fig. 1). As one can see, the He-inlet temperature T₃ remains on the planned constant value of 14.5 K within the foreseen heat load range. Furthermore it can be seen that the measured heat load values in both cases of different He-throughputs are about 20% higher than the calculated ones. In this

manner the good agreement between the calculated and measured values has been demonstrated.

Moreover the temperature stability of the thermosyphon circuit was tested under several constant heat loads and in a no load run corresponding to the situation of the cooled down cold neutron source in the case of a shut down reactor. In all cases the temperature stability was found to be within ± 0.2 K during a measuring time of about 8 hours for each test.

Figure 7 shows the temperature response at the He/H₂ heat exchanger to a 600 W heat load step on the moderator chamber. As one can see, in the more important case of heat loading the settling time is relative short in comparison to the time in case of heat relieving.

Fig. 7 Temperature response at the He/H₂ heat exchanger to a 600 W heat load pulse

Even under such extreme conditions the thermosyphon circuit showed a "good natured" and stabile behavior.

In a further test the temperature control has been switched off leading to the same consequence as a temperature control failure. In this case the He inlet temperature T_3 at the He/H₂ heat exchanger, in standard operation kept on 14.5 K, can drop together with the H₂-temperature of the thermosyphon circuit below the H₂ solidification temperature 13.9 K. In consequence the H₂ circuit can be interrupted by H₂ ice plugs and the moderator chamber is not cooled any more. As a result of this test an interruption of the H₂ circuit was watched only below a moderator chamber heat input of 350W by increasing the H₂ system pressure. But because of the heat input of more than 450W during the 4MW reactor operation such an incident has no relevance.

Another incident - lack of the cold power - was simulated by a refrigerator shut down during continous 600 W heat input on the moderator chamber. As a consequence the temperature of the moderator chamber increased from 20 to 200 K within 30 minutes. That means a very good emergency cooling property of the thermosyphon circuit, which is due to the cold capacity of the 100 kg He/H₂ heat exchanger and the ability of the H₂ thermosyphon to a high heat transfer under H₂ gas flow conditions.

As a last test the LH₂ was blown out of the H₂-system by He gas. No excessive pressure rise in the H₂-system occured in this procedure which is foreseen to transform the H₂-system in inert conditions in cases of safety relevant incidents.

V REFERENCES

1. R.D. Mc Carty, "Hydrogen Technological Survey-Thermophysical Properties", 1975, NASA SP -3089
2. R. D. Mc Carty, " Thermophysical Properties of Helium-4 from 2 to 1500 K with Pressures to 1000 Atmospheres". NBS Technical Note, Issued Nov. 72

3. VDI - Wärmeatlas, "Berechnungsblätter für den Wärmeübergang", 3. Auflage 1977, Verlag des Vereins Deutscher Ingenieure, Düsseldorf.
4. I. Klipping, "Datensammlung zur Kryotechnik" VDI - Lehrgang Kryotechnik, 24.-28. Feb. 1975 in Düsseldorf
5. W. Kast, O. Krischer, H. Reinicke, K. Wintermantel, "Konvektive Wärme- und Stoffübertragung", Springer Verlag Berlin 1974
6. Vereinigung der Technischen Überwachungsvereine e.V., Essen, "AD-Merkblätter", Carl Heymanns Verlag KG, Köln
7. F. Mayinger, "Strömung und Wärmeübergang in Gas-Flüssigkeits-Gemischen", Springer Verlag Wien 1982
8. F. Stelzer, "Wärmeübertragung und Strömung", Verlag Karl Thiemig KG, München, 1971

The Cold Neutron Multiplication of the Cold Neutron Source (CNS) at IAE, Beijing

Dr. An. Sun. Yu
Institute of Atomic Energy
China

ABSTRACT

The Heavy Research Reactor (HWRR) at the Institute of Atomic Energy, Beijing is rated at 10 MW, and can be boosted to 15 MW with the maximum thermal neutron flux of 2×10^{14} n/cm². Six horizontal experimental beams are provided and four of them have been used for the neutron diffraction and scattering experiment. For carrying on studies on biological macromolecules, polymers, microstructures of metallic alloys, etc. with small neutron scatter, a liquid hydrogen CNS is now available with the reactor^[1]. CNS was completed in September 1988 in cooperation with the cryogenic Lab, CAS, and CEA, France.

Experience on the CNS design, construction, and safety regulation at CEA, France, in particular those of CNS with the reactor EL-3 at Saclay, have been drawn upon in the design of our CNS. The cold cell with 11 cm in diameter and 5 cm in thickness is inserted into the end of the No. 4 beam hole, close to the reactor core. In the hydrogen system, evaporated hydrogen from the cold cell is recondensed in the condenser through heat exchange with cold helium gas from the refrigerator. Circulation of hydrogen is sustained by thermo-syphoning due to the density difference between the liquid hydrogen in the tubing leading to the cell and the two-phase hydrogen in the tubing leading back to the condenser. The amount of liquid hydrogen in the cold cell has

been measured to be about 80% full under simulated nuclear heating by ^{137}Cs gamma absorption method.

When CNS had just been finished, the cold neutron multiplication was measured in front of the beam hole with a beryllium filter neutron detector. We counted neutrons for cold cell with and without liquid hydrogen respectively. The result showed that the average multiplication for neutrons with a wavelength greater than $3.5 \text{ \AA}$ is 12.

After a 27-m neutron guide had been set up at the exit of the guide, we measured the neutron spectrum with and without cold source by time-of-flight method, from which we calculated the average multiplication of neutrons with a wavelength greater than $3.5 \text{ \AA}$ to be 12.6, in good coincidence with that from the beryllium filter detector. We also deduced the neutron multiplication as a function of wavelength. Comparing the results of ours with those of EL-3 and the Orphee Reactor in France, it seems to us that our CNS is better than that of the EL-3 Reactor and nearly comparable to that of the Orphee Reactor. One of the main differences between CNS of HWRR (IAE) and that of EL-3 (Saclay) is the thickness of the cold cell, which is 7 cm for EL-3 CNS, and 5 cm for Orphee and ours. So, 5 cm is a better dimension of cold cell thickness for neutron multiplication.

We would like to thank Dr. B. Farnoux for his helpful discussion.

REFERENCES

1. Y. Zhou et al, "The Cryogenic System for the Cold Neutron Source at the Institute of Atomic Energy, Beijing.". to be published

The Cornell University Cold Neutron Beam Facility: Design Features

David D. Clark, Takashi Emoto, Carol G. Ouellet, Elissa Pekarul, J. Scott Berg***
Cornell University, Ward Laboratory of Nuclear Engineering
Ithaca, New York, USA 14853-7701

ABSTRACT***

An ultra-low-background facility for basic and applied neutron beam research is being built at the Cornell 500-kW TRIGA reactor. The beam is to be obtained by a curved 13-m neutron guide to filter out fast neutrons and gamma rays from the core, with the neutrons entering the 2-cm by 5-cm guide coming from a cold neutron source of mesitylene at ~40K to increase transmission through the guide. Optimization of the cold source, within the limits set by design criteria and geometrical restrictions, has involved Monte Carlo simulations to choose source shape and size, and measurements and estimation of nuclear heating and shielding requirements have been made. The design criteria, which include considerations of simplicity and safety of cold source operation at a medium-power reactor on a university campus, are described. Results to date of design studies and low-power trials are presented. Final design choices are imminent and completion of the facility is anticipated for early fall 1990.

I. INTRODUCTION

The purposes and general features of the facility have been described previously and in some detail elsewhere, most recently⁽¹⁾ at the Fifty Years with Nuclear Fission Symposium in

*Now at Nuclear Engineering Teaching Laboratory, University of Texas at Austin

**Now at Physics Department, Stanford University

***Supported in part by DOE Grant No. DE-FG07-89ER12897

Gaithersburg in April 1989. Projected uses are in experiments that require ultra-low backgrounds; examples include capture gamma and conversion electron spectroscopy for the investigation of level schemes and nuclear reactions and applications such as prompt gamma activation analysis and neutron depth profiling. These experiments pose somewhat different design requirements than for atomic structure investigations that utilize the long wavelengths of cold neutrons. Because the reactor is located on a university campus and the operating staff is small, safety and simplicity of operation and maintenance are prime considerations. The cold source and associated components form a unitary assembly with a removable 6-inch OD beamplug. To avoid hazards associated with liquid hydrogen or solid methane, mesitylene, a liquid at room temperature, was chosen. (Since we do not require the coldest or purest spectra, mesitylene can be seen to be a satisfactory cold moderator for our purposes from spectra obtained by Utsuro, Sugimoto, and Fujita⁽²⁾.) To simplify operation and to avoid circulating cryogenic fluids inside the beamport, cooling of the mesitylene is by copper cold fingers connected to a cryogenic refrigerator outside the reactor shield. Further details and references to earlier work by others on cold sources and neutron guides are in Ref. 1.

Two parts of the design and testing program are discussed here. One concerns determining a geometry of the cold moderator chamber that optimizes the yield of subthermal neutrons. The final choice was a 3.75-cm-radius, 3.0-cm-thick disk, without a re-entrant hole. The second concerns measuring and minimizing nuclear heating of the mesitylene, its aluminum chamber, and indeed the cold fingers themselves. The heating is primarily by gamma rays, with fast neutron elastic scattering causing additional energy deposition in the cold moderator. It was found that lead shielding would be necessary.

II. OPTIMIZATION OF THE COLD SOURCE GEOMETRY

The geometry was studied using Monte Carlo simulation. Because chamber dimensions are not much larger than several mean free paths and because complex geometries such as re-entrant holes were to be considered, a Monte Carlo method was the most appropriate. An isotropic 330K Maxwellian flux was assumed to be incident on the moderator disk from all sides. Double-differential cross sections for neutron scattering by hydrogen in cold mesitylene are not available, but Utsuro⁽³⁾ has analyzed data from experiments on total neutron scattering by 10K mesitylene in terms of effective masses, energies of modes of molecular motion, and scattering cross sections per H atom, all as functions of energy. For a neutron of any given energy entering a collision with hydrogen, we used his cross section for the probability of collision with hydrogen, and treated the struck hydrogen as a heavy gas of the corresponding effective mass with an energy distribution for the deduced modes at the physical temperature of the moderator. This procedure gave the new energy and direction of the scattered neutron after each collision.

The history of each neutron was followed until it was absorbed or escaped from the disk.

Within the accuracy of the model, the ratio of flux of emerging cold (<10 meV) neutrons to the incident warm flux varies from 0.19 to 0.34 for a variety of reasonable geometries. The fraction of the emerging spectrum that is below 10 meV varies from 0.61 to 0.88. For feeding the guide, the neutrons that matter are those leaving the face of the source towards the guide at angles with respect to the guide axis equal to or less than the critical angle for total reflection. Although a re-entrant hole in the disk makes the spectrum closer to a Maxwellian, it does not increase the yield of these forward cold neutrons, and the presence of a non-Maxwellian tail of warmer neutrons does not alter the utility of the source for our purposes. These calculations, although based on a somewhat simplified model, are considered adequate for their intended purpose, that of comparing different shapes and sizes. They were done with Turbo Pascal under MS-DOS on a DEC Rainbow. A rough estimate of the cold flux at the guide tube exit can also be made. Expressed in the conventional terms for calculating reaction rates, it is equivalent to a flux of $\sim 10^7$ neutron/cm² sec of 2200 m/sec neutrons.

III. NUCLEAR HEATING AND SHIELDING

Before undertaking detailed design of the facility, a low-power test run of a cold chamber and a 5-m guide was conducted in November 1988. Unacceptably large nuclear heating effects were observed. Subsequent analysis and neutron and gamma-ray flux measurements showed that gamma-ray heating was the dominant cause. Final design work has concentrated on reducing gamma-ray heating by suitable downsizing and placement of components and by use of gamma-ray shielding.

Measurements of thermal, resonance, and fast neutron fluxes were taken with Au, Cd-covered Au, and Ni threshold activation foils, respectively. Direct measurement of gamma-ray heating was done by monitoring with thermocouples the temperature rise of Cu, Al and organic samples suspended by stainless-steel wires in an evacuated chamber at positions surrounding the proposed source location. The values obtained in this way could easily be extrapolated to predict values for full-sized components at various positions. The contribution of neutrons of any energy to the heating was calculated from the activation data to be small for the metals, but elastic scattering of fast neutrons was calculated to make a non-negligible contribution in heating the moderator itself. Measured fluxes (extrapolated to 500 kW) at 20 cm from the core edge, a possible location of the moderator chamber, are 1×10^{12} thermal, 1×10^{10} resonance, and 2.1×10^{10} fast neutrons/cm² sec and 1×10^3 rad/sec gamma-ray dose rate in the unshielded case. With the proposed lead shield (see the next section), the corresponding estimated fluxes are 0.7×10^{12} , 0.9×10^{10} , 0.8×10^{10} , and 0.3×10^3 . The corresponding heating effects in watts per

gram are 10 mW/g due to gamma rays and 2.8 mW/g due to fast neutrons in the unshielded case; with shielding these would be 3 mW/g and 1mW/g respectively. The deduced heat load of the original chamber in the 1988 trial extrapolated to 500 kW was 30 watts. That chamber was a 5.9-cm-radius, 5.0-cm-thick disk with a 2.5 by 5.7 by 3.0 cm deep re-entrant hole. It was made of 1190 g of aluminum, stainless steel, and copper and contained 440 g of mesitylene. In the current smaller design the chamber is made of 86 g of aluminum and contains 100 g of mesitylene. The estimated heat load for it, with lead shielding, would be 0.7 watts, 0.4 in the mesitylene and 0.3 in the Al chamber.

IV. HEAT REMOVAL

The heat load on the cryogenic refrigerator due to nuclear heating of the chamber is not large compared to the capacity of commercially available refrigerators of reasonable cost. It is the conductivity of the cold fingers, even if made of OFHC copper, that turns out to be the limiting factor. With the restricted space available in the beamport for the cold fingers and their coaxial copper heat shields, the design choice is two cold fingers, each of 9/16-inch diameter. For example, the required temperature drop along the 270 cm from the chamber to the refrigerator would be 84K to conduct a heat load of 10 watts, and the moderator would therefore be at 104K even if the refrigerator were at 20K. Nuclear heating of the cold fingers themselves at their chamber end can add another several tens of kelvins if there is inadequate gamma-ray shielding. The necessity to shield the moderator and the cold fingers at the upstream end is clear. We have chosen to use a cylindrical lead cap with 0.5-inch side walls and a 3-inch thick upstream end to surround the chamber and cold fingers for the portion of the assembly that is within the graphite reflector region. Nuclear heating with the lead present will be measured before the design is finalized. If necessary as a last resort, the entire beamplug can be withdrawn a small distance to obtain an acceptable source temperature of 40K (but at the cost of reduced output flux).

V. RADIATION EFFECTS

The radiation fluxes discussed in the previous section can lead to radiolysis of the mesitylene. There is no available data on this for the conditions of the proposed operation, but from data for room temperature gamma-ray irradiation⁽⁴⁾ and for cold temperature fast neutron irradiation⁽⁵⁾, one can get an estimate that 3×10^{-9} STP liters of H_2 would be produced per gram per second at 500 kW in the current size of cold source, with lead shield. This corresponds to 300 rad/sec of gamma rays and 100 rad/sec of fast neutrons. Our reactor normally operates on a one-shift five-day week; with a projected duty cycle of operating the cold source for a maximum of two weeks at a time before warming up and draining the mesitylene, the accumulated hydrogen in the 100 g

of mesitylene in the source would be ~0.1 STP liter. This amount should not cause any problem. Because the equilibrium temperature of the source will be about 40K, it is not expected that any other stored energy problems will arise. Nevertheless, the mesitylene will be monitored closely in the initial operation of the source to measure the extent of any observable radiation effects.

VI. SUMMARY

The design studies and low-power tests of a proposed cold neutron beam facility that have been presented show that it appears feasible to build and operate at a medium-power university reactor with a small operating staff a facility for high-quality basic and applied neutron beam research.

VII. REFERENCES

1. David D. Clark, Takashi Emoto, Carol G. Ouellet, Elissa Pekar, J. Scott Berg, "The Cornell University Cold Neutron Beam Facility", in 50 Years with Nuclear Fission, eds., J. W. Behrens and A. D. Carlson, American Nuclear Society (1989), pp. 855-860.
2. Masahiko Utsuro, Masaaki Sugimoto, Yoshiaki Fujita, "Experimental Study on a Cold Neutron Source of Solid Methylbenzene", Annu. Rep. Res. Reactor Inst. Kyoto Univ. **8**, 17-25 (1975).
3. Masahiko Utsuro, "A simple neutron scattering study of proton motion in methyl compounds", J. Phys. C: Solid State Phys. **9**, L171-L175 (1976).
4. J. Weiss, N. Carciello, J. Sucher, "Radiolysis of Aromatic Compounds", pp. 61-62 in Annual Report, Nuclear Engineering Department, Brookhaven National Laboratory, December 31, 1966.
5. Masahiko Utsuro, Masaaki Sugimoto, "Pulsed Cold Source of Solid Methylbenzene", J. of Nucl. Sci. and Tech. **14** [5], pp. 390-392 (1977).

The LANSCE Target System

Gary J. Russell, Harold Robinson, and H. Grady Hughes

Los Alamos National Laboratory
Los Alamos, New Mexico USA

ABSTRACT

The LANSCE target system is a high-performance, pulsed-spallation neutron source that provides neutron beams for materials science research. The unique LANSCE split-target/flux-trap-moderator design performs exceedingly well and has operated without a target or moderator change for over four years at nominal proton currents of $\approx 50 \mu\text{A}$ of 800-MeV protons. We did an extensive computer simulation of the as-built LANSCE Target-Moderator-Reflector-Shield geometry and have used this mockup in a Monte Carlo calculation to predict the LANSCE neutronic performance. LANSCE-predicted moderator intensities (per proton) for a tungsten target are essentially the same as ISIS-predicted moderator intensities for a depleted uranium target.

INTRODUCTION

The Manuel Lujan, Jr. Neutron Scattering Center (LANSCE)¹ is a state-of-the-art pulsed spallation neutron source. The origin of the 800-MeV protons for LANSCE is the Clinton P. Anderson Meson Physics Facility (LAMPF)². LAMPF 800-MeV protons feed the *Proton Storage Ring* (PSR)³ which produces short (250 ns), intense proton-pulses for LANSCE. An international user community utilizes LANSCE for condensed matter and nuclear physics research. The LANSCE target system needs to be operated efficiently and continually upgraded to remain competitive

worldwide. The LANSCE Target-Moderator-Reflector-Shield (TMRS)⁴ provides spectrometers with potent neutron beams with appropriate time-structure and energy-spectral distributions.

Figure 1 depicts the LANSCE TMRS. Presently, there are four slab-moderators in flux-trap geometry between the split targets. The four flux-trap moderators service twelve existing flight paths. The LANSCE TMRS has four unique features:

- o There is *no crypt* per se (void region) surrounding the TMRS.
- o The target is *not in one piece* but split into two unequal segments separated by a void.
- o Moderators are *not* located adjacent to the target as in the more conventional wing-geometry design. In the LANSCE target system, the moderators are located in a flux-trap arrangement in which there is no target material. They lie *between* the two target segments and surround a central void region.
- o A conventional all-beryllium reflector is *not used*; the LANSCE TMRS employs a composite (beryllium/nickel) reflector/shield.

One significant advantage of our flux-trap geometry is that all four flux-trap moderators are high intensity. This is in contrast to conventional wing-geometry moderators employed at ISIS⁵ and IPNS.⁶ At the latter spallation sources, moderators are located at both the front and back of the target to increase the number of flight paths serviced simultaneously. Because neutron production from spallation targets is strongly dependent on axial location, moderators in the fore position are nominally a factor of two more intense than aft-placed moderators. This relative performance of fore and aft moderators in wing-geometry has been predicted theoretically⁷ and observed experimentally. LANSCE flux-trap moderator neutronic performance is akin to the neutronic performance of high-intensity, wing-moderators.

Figure 2 depicts the twelve existing LANSCE neutron flight paths. Figure 3 shows the four LANSCE TMRS flux-trap moderators; each moderator services three flight paths. Three of the moderators are chilled (~290 K) light water. Two of the water moderators are heterogeneously poisoned with gadolinium at 2.5 cm from the exit face and have cadmium decoupler/liners. We call these two moderators "high-intensity" moderators. The third water moderator is heterogeneously poisoned with gadolinium at 1.5 cm and has a boron decoupler/liner (1/e transmission at ≈ 3 eV). We refer to this moderator as the "high-resolution" moderator.

The *poison* neutronically defines (for neutrons with energies below some cutoff energy) the thickness of a moderator viewed by an experiment. *Decouplers* surround a moderator and neutronically isolate it (for neutrons below some cutoff energy) from the reflector. *Liners* neutronically isolate the moderator "viewed surface" from the reflector/shield. The type, thickness, and depth of a poison material (together with the types and thicknesses of decoupler and liner materials) determine the time-shape of neutron pulses. One job for target-system designers of spallation neutron source is to minimize the trade-offs between intensity and time-resolution to maximize the neutronic performance of moderators.

We recognize the importance of cold neutrons in condensed matter research; our fourth flux-trap moderator is liquid para-hydrogen at ≈ 20 K. The liquid hydrogen moderator has no poison, a gadolinium decoupler, and a cadmium liner.⁴

The LANSCE TMRS was installed in August 1985 and has operated reliably (with no target or moderator changes) since its inauguration. Proton currents over the four-year period were a nominal $50 \mu\text{A}$.

CALCULATIONS AND RESULTS

Because the LANSCE TMRS is an innovative design (unique worldwide) for a spallation neutron source, it is imperative that we both measure⁸ and calculate the neutronic performance of the as-built LANSCE target system. During the design phase of the LANSCE target system, Russell^{4,7} did preliminary calculations to estimate the neutronic performance. To directly compare measured and calculated neutron performance, Hughes⁹ did a very detailed geometric mockup of the as-built LANSCE TMRS. We used the powerful Los Alamos Monte Carlo code system¹⁰ to calculate the neutronic performance of LANSCE. Reference 11 gives comparisons between predicted and measured LANSCE moderator neutronic performance. We must also compare the LANSCE absolute neutronic performance with those of spallation neutron sources using conventional wing-geometry design; this comparison has been done in Ref. 11.

Prael¹² incorporated into the Los Alamos Monte Carlo code system the ability to perform point-detector computations using thermal neutron-scattering kernels. We employed this powerful capability to predict the neutronic performance of the LANSCE moderators. Figure 4 shows the results. Below ~ 20 meV, the liquid hydrogen moderator has the highest neutron leakage. Below

~300 eV, the trade-off in thermal neutron leakage between the high-resolution and high-intensity water moderators is readily seen. Note that for energies >1eV, neutron leakage from the liquid hydrogen moderator equals that from the high-intensity water moderator.

Because LANSCE is a pulsed-spallation neutron source, the time behavior of neutrons is also of paramount importance. To get a more complete picture of moderator performance, one must look at neutron pulse widths in addition to neutron leakage. Such comparison is beyond the scope of this paper, but they have been made elsewhere.^{4,7}

ACKNOWLEDGEMENTS

We appreciate the support of Roger Pynn for this work. We thank Tatia Vander Maat for her typing and Maria DiStravolo for proofreading the text. LANSCE work is supported by the US Department of Energy, Office of Basic Energy Sciences, under contract W-7405-ENG 36 with the University of California.

REFERENCES

1. R. Pynn, "Recent Progress at LANSCE," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X)*, Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 47-52.
2. M.S. Livingston, "LAMPF, a Nuclear Physics Research Facility," Los Alamos National Laboratory report LA-6878-MS (1977).
3. R. J. Macek, "The Proton Storage Ring: Problems and Solutions," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X)*, Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 91-122.
4. G. J. Russell, H. Robinson, G. L. Legate, R. Woods, E. R. Whitaker, A. Bridge, K. J. Hughes, and R. D. Neef, "The LANSCE Target System," in *ICANS-IX, Proceedings of the Ninth Meeting of the International Collaboration on Advanced Neutron Sources*, F. Atchison and W. Fischer, Eds., (Swiss Institute for Nuclear Research, Villigen, Switzerland), ISBN 3-907998-01-4, pp. 177-244 (April 1987).
5. A. Carne, "Review of the SNS Target Station," in *ICANS-IV, Proceedings of the Fourth Meeting of the International Collaboration on Advanced Neutron Sources*, Y. Ishikawa, N. Watanabe, Y. Eudoh, N. Niimurah, and J. M. Newsam, Eds., KENS Report II, pp. 136-153 (March 1981).

6. J. M. Carpenter, C. W. Potts, and G. H. Lander, "Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL): A Status Report as of June 1982," in *ICANS-VI, Proceedings of the Sixth Meeting of the International Conference on Advanced Neutron Sources*, (Argonne National Laboratory, Argonne, Illinois), ANL-82-80, pp. 77-101 (January 1983).
7. G. J. Russell, C. D. Bowman, E. R. Whitaker, H. Robinson, and M. M. Meier, "LANSCE High Power (200 μ A) Target-Moderator-Reflector-Shield", in *ICANS-VIII, Proceedings of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources*, G. C. Stirling, Ed., (Rutherford Appleton Laboratory, Chilton Didcot, England), RAL-85-110, pp. 272-293 (November 1985).
8. J. S. Gilmore, R. A. Robinson, and G. J. Russell, "Experimental Determination of Neutron Beam Fluxes at LANSCE from Gold Foil Activation," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X)*, Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 469-472.
9. H. G. Hughes, III, "Monte Carlo Simulations of the As-Built LANSCE Target/Moderator/Reflector/Shield Geometry," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X)*, Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 455-468.
10. R. E. Prael and H. Lichtenstein, "User Guide to LCS: The LAHET Code System." Los Alamos National Laboratory report LA-UR-89-3014 (September 1989).
11. G. J. Russell, "LANSCE Target System Performance," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X)*, Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 483-496.
12. R. E. Prael, private communication.

Fig. 1. Illustration of the LANSCE target system consisting of a split-target, an inner beryllium reflector region, and an outer nickel reflector/shield. Three water slab-moderators and a liquid hydrogen slab-moderator are in flux-trap geometry between two tungsten targets. The system is one meter in diameter and one meter high.

Fig. 2. Plan-view of the LANSCE neutron beamline arrangement.

Fig. 3. Expanded plan-view schematic of the LANSCE moderator arrangement. The liquid hydrogen moderator is depicted on the right side.

LANSCCE As-Built Target-Moderator-Reflector-Shield (TMRS) Calculated Moderator Neutronic Performance

Fig. 4. Calculated neutron leakage spectra for the LANSCE high-intensity and high-resolution light-water, and liquid hydrogen moderators.

Evaluation and Validation of Neutron Cross-Sections for Liquid Hydrogen and Deuterium for the Design of Cold Neutron Sources

W. Bernnat, D. Emendörfer, J. Keinert, M. Mattes

Institut für Kernenergetik und Energiesysteme (IKE), University of Stuttgart,
Pfaffenwaldring 31, D-7000 Stuttgart 80, West Germany

ABSTRACT

The scattering kernels for molecular hydrogen and deuterium gas derived by Young and Koppel have been generalized for the liquid state by including harmonic vibrations and hindered translations as well as the interference of neutron waves from different molecules. The frequency spectrum for the harmonic vibrations was taken from experimental and theoretical investigations. For the intermolecular interference a combination of static structure factors derived from hard core and Lenard Jones interaction was used. Both differential and integral cross-sections evaluated by the generalized scattering kernels show a sufficiently good agreement with corresponding experiments. Calculated neutron spectra and cold neutron gain factors for liquid H_2 or D_2 show a good agreement with experiments too. The scattering laws $S(\alpha, \beta)$ for ortho- and para-hydrogen and deuterium respectively are represented now in the ENDF-6 format.

I. INTRODUCTION

Design and optimization calculations for cold neutron sources should be based on reliable nuclear data. For the case of cold sources with H_2 or D_2 in the liquid state the corresponding scattering kernels should take into account a generalized translational movement of the molecules by superposition of harmonic vibrations and hindered translation (e.g. by using an effective mass) but also the intermolecular interference of neutron waves from

different molecules, as a consequence of the short range order in the liquid. The well-known scattering kernels of Young and Koppel [1] take into account only the free translation of molecules and are valid only for H_2 , D_2 in gaseous form (e.g. in supercritical cold neutron sources). The scattering kernels for H_2 and D_2 in the liquid state can be formulated explicitly [2,3]. The double-differential neutron cross-sections can be written for ortho-, para-hydrogen and -deuterium as:

Para-hydrogen (spin $S = 0$):

$$\frac{d^2\sigma}{d\Omega d\epsilon} = \frac{k}{k_0} \left[b_{coh}^2 S(\vec{\kappa}) S_{ee}^{liq.}(\vec{\kappa}, \epsilon) + b_{inc}^2 S_{eo}^{liq.}(\vec{\kappa}, \epsilon) \right] \quad (1)$$

Ortho-hydrogen (spin $S = 1$):

$$\begin{aligned} \frac{d^2\sigma}{d\Omega d\epsilon} = & \frac{k}{k_0} \left\{ \frac{1}{3} b_{inc}^2 S_{oe}^{liq.}(\vec{\kappa}, \epsilon) + \right. \\ & \left. + \left[b_{coh}^2 S(\vec{\kappa}) + \frac{2}{3} b_{inc}^2 \right] S_{oo}^{liq.}(\vec{\kappa}, \epsilon) \right\} \end{aligned} \quad (2)$$

Ortho-deuterium (spin $S = 0, 2$):

$$\begin{aligned} \frac{d^2\sigma}{d\Omega d\epsilon} = & \frac{k}{k_0} \left\{ \left[b_{coh}^2 S(\vec{\kappa}) + \frac{5}{8} b_{inc}^2 \right] S_{ee}^{liq.}(\vec{\kappa}, \epsilon) + \right. \\ & \left. + \frac{3}{8} b_{inc}^2 S_{eo}^{liq.}(\vec{\kappa}, \epsilon) \right\} \end{aligned} \quad (3)$$

Para-deuterium (spin $S = 1$):

$$\begin{aligned} \frac{d^2\sigma}{d\Omega d\epsilon} = & \frac{k}{k_0} \left\{ \frac{3}{4} b_{inc}^2 S_{oe}^{liq.}(\vec{\kappa}, \epsilon) + \right. \\ & \left. + \left[b_{coh}^2 S(\vec{\kappa}) + \frac{1}{4} b_{inc}^2 \right] S_{oo}^{liq.}(\vec{\kappa}, \epsilon) \right\} \end{aligned} \quad (4)$$

In the partial scattering laws $S_{eo}^{liq.}(\vec{\kappa}, \epsilon)$ for the liquid phase translational modes are combined with molecular ones by convolution, compatible with conservation of energy and momentum in the collision (abbreviations: e=even, o=odd):

$$S_{eo}^{liq.}(\vec{\kappa}, \epsilon) = \sum_{J=even} P_J \sum_{J'=odd} (2J'+1) \sum_{n=0}^{\infty} \frac{1}{n!} \left(\frac{\kappa^2 \hbar}{4M_{p,d}\omega} \right)^n \cdot \sum_{l=|J'-J|}^{J'+J} |A_{nl}|^2 C^2(JJ'l; 00) S_{Transl.}^{liq.}(\vec{\kappa}, \epsilon_{nJJ'}) \quad , \quad (5)$$

with

$$\epsilon_{nJJ'} = \epsilon + n\hbar\omega + E_{J'} - E_J \quad .$$

The matrix elements A_{nl} are defined as

$$A_{nl} = \int_{\mu=-1}^{+1} P_l(\mu) \mu^n e^{-\frac{\mu^2 \kappa^2 \hbar}{8M_{p,d}\omega} + i\frac{\kappa R_0 \mu}{2}} d\mu \quad .$$

$C^2(JJ'l; 00)$ denote Clebsch-Gordan coefficients. The scattering law evaluations according equations (1) to (5) are carried out in the specially developed computer code SCATHD [2].

The required scattering law $S_{Transl.}^{liq.}(\vec{\kappa}, \epsilon_{nJJ'})$ for the generalized translational movement can be calculated in advance from the corresponding intermediate scattering function by a numerical Fourier transform e.g. by the code GASKET [4]. The frequency distributions for the harmonic vibrations of the molecules in liquid H_2 and D_2 are chosen in accordance with data derived from experimental and theoretical investigations (Fig. 1).

Fig. 1: Frequency distributions of the translational modes of liquid hydrogen and deuterium

The short range order between the molecules in the liquid we have taken into account by a synthetic structure factor $S(\vec{\kappa})$, determined for small momentum transfers by a pair distribution function with hard core interaction, and for large momentum transfers by a

pair distribution function with Lenard-Jones interaction (Fig. 2). The corresponding pair distribution function is shown in Fig. 3. The structure factor was chosen in such a way that the characteristic decrease in the total cross-section of para-hydrogen and normal

Fig. 2: Static structure factors of liquid hydrogen and deuterium **Fig. 3:** Pair distribution functions $g(r)$ of liquid hydrogen and deuterium

deuterium between 3 and 1 meV – due to intermolecular interference – is represented to a reasonable degree of accuracy (Fig. 4 through Fig. 6). As one can see from these figures the total cross-sections evaluated from the liquid kernels agree considerably better with the measured ones than those derived from the Young-Koppel kernel.

Fig. 4: Total neutron cross-sections for para-hydrogen at $T = 14$ K

Fig. 5: Total neutron cross-sections of $n\text{-H}_2$ at $T = 16$ K

In Fig. 7 through Fig. 9 double differential and differential cross-sections evaluated from different kernels are compared with measurements. Also for the differential cross-sections the agreement with the measurement is generally better with data derived from the liquid kernel compared with those derived from the Young-Koppel kernel.

Fig. 6: Total neutron cross-sections for normal-deuterium at $T = 19$ K

Fig. 7: Double differential neutron scattering cross-sections of $n\text{-H}_2$ at $T = 18$ K ($E_0 = 2.9$ meV, $\vartheta = 45^\circ$)

Fig. 8: Double differential neutron scattering cross-sections of 52% $p\text{-H}_2$ at $T = 19.8$ K ($E_0 = 21.8$ meV, $\vartheta = 43.9^\circ$)

Fig. 9: Differential neutron scattering cross-sections of 3.1% $p\text{-D}_2$ at $T = 20$ K ($E_0 = 81.8$ meV)

The scattering law for proton and deuteron in liquid hydrogen and deuterium

$$S(\alpha, \beta) = e^{\frac{\beta}{2}} S(\vec{\kappa}, \epsilon)$$

$$\alpha = \frac{\kappa^2 \hbar^2}{2M_{p,d} kT}, \quad \beta = \frac{\epsilon}{kT}$$

has been generated in the ENDF-6 format for a fine (α, β) -grid and different temperatures. Since as a consequence of the spin-dependence of the nuclear reaction the principle of detailed balance is not generally fulfilled, the scattering law data must be given for both positive and negative β -values in evaluated data files. The (α, β) -grids for the scattering laws (and partial scattering law) have to be chosen carefully to get numerically reliable results.

II. COMPARISON OF MEASURED AND CALCULATED NEUTRON SPECTRA

As a data basis for neutron spectra calculations we have generated multigroup cross-sections and scattering matrices for the thermal range with the code NJOY-89 (with modifications). For the fast energy range and for reflector and structure materials JEF-1 data were used. The large number of groups in the basic multigroup libraries (100 fast, 176 thermal) were reduced to 102 for 1D-3D-spectral calculations using a multigroup spectrum generated by the spectral code RSYST/CGM.

The liquid state characteristically influences the energy dependence of the neutron spectra. While the Young-Koppel kernel for H_2 and D_2 in the gaseous phase takes into account the effects of the chemical binding in the molecule only, the liquid kernel accounts for the interaction between the molecules in addition. Therefore in the real liquid the slowing down power is smaller than predicted from the Young-Koppel gas kernel. The consequence is that in infinite media the molecular gas kernel produces neutron spectra that are too soft. This means that the Young-Koppel kernel overestimates the number of cold neutrons. This effect even is seen in the leakage spectra of a real liquid hydrogen cold neutron source (Fig. 10). The ratio of the corresponding gain factors is displayed in Fig. 11. At energies lower than 1 meV the Young-Koppel kernel overestimates the gain factor by up to 80 %.

Fig. 10: Comparison of calculated and measured [7] neutron leakage spectra of a liquid hydrogen neutron source (32.8 % p-H₂) at T = 20 K

Fig. 11: Ratio of gain factors calculated by the Koppel-Young and the intermolecular model (IKE INTER) of a liquid hydrogen cold neutron source (32.8 % p-H₂) at T = 20 K

In calculating neutron spectra for finite media, in addition to the differences from the slowing down properties we experienced differences from the transport properties of the gas- and liquid-kernels. As can be judged from Fig. 4, as a consequence of intermolecular interference in liquid deuterium, the mean free path of cold neutrons derived from

the liquid kernel is remarkably larger than the mean free path from the Young-Koppel kernel. Therefore in calculated leakage spectra the transport effects may overcompensate the slowing down effects, so that the Young-Koppel scattering model, which does not care for intermolecular interference, now will underestimate the number of cold neutrons. This tendency can be seen from the leakage spectra (Fig. 12) and the gain factor for a liquid deuterium source (Fig. 13).

Fig. 12: Comparison of calculated and measured [8] neutron leakage spectra of a liquid deuterium cold neutron source ($n\text{-D}_2$) at $T = 23\text{ K}$

Fig. 13: Comparison of calculated and measured [8] gain factors of a liquid deuterium cold neutron source ($n\text{-D}_2$) at $T = 23\text{ K}$

The gain factors of cold neutron sources with heavy water reflectors are strongly influenced by the choice of the scattering dynamics model of D in D_2O [2,9]. Substituting the commonly used incoherent approximation by cross-sections considering the coherent scattering (Fig. 14), the gain factor decreases by about 20 % at a neutron wavelength of 10 Å.

Fig. 14: Total neutron cross-sections of D_2O at room temperature

The improved cross-sections lead to a remarkably better agreement of calculated spectra with measured spectra for both liquid hydrogen and deuterium compared to calculations based on the Young-Koppel model. Comparisons of Monte Carlo calculations with experiments showed that spectra in the beam tube of the cold neutron source can be determined sufficiently accurate even if the geometry of the cold source is very complex.

III. CONCLUSIONS

The comparisons of calculated cross-sections and neutron spectra with measurements have shown that the described scattering kernels for liquid hydrogen and deuterium are a reliable basis for design and optimization calculations for cold neutron sources. For moderators in the liquid state therefore these kernels should be used rather than the Young-Koppel kernel. Scattering laws for liquid hydrogen and deuterium (ortho- and para-modification) for both boiling temperature and melting temperature at 0.1 Mpa are available in ENDF-6 format. For convenience, point-wise files (PENDF) for further processing in NJOY are available too to avoid problems in processing scattering laws with negative β -values and large negative exponents.

IV. ACKNOWLEDGEMENT

This work has been funded by the German Federal Minister for Research and Technology (BMFT) under the contract no. F3/55/03EM1STU-0.

V. REFERENCES

- [1] J.A. YOUNG and J.U. KOPPEL, "Slow Neutron Scattering by Molecular Hydrogen and Deuterium", Phys. Rev. 135, A603 (1964).
- [2] W. BERNNAT, D. EMENDÖRFER, J. KEINERT und M. MATTES, "Flüssigkeitsmodelle für die Neutronenstreuung an Wasserstoff und Deuterium unter Berücksichtigung der innermolekularen und zwischenmolekularen Interferenz", IKE 6-175, IKE Stuttgart (1989).
- [3] W. BERNNAT, D. EMENDÖRFER, J. KEINERT and M. MATTES, "Evaluation of Neutron Cross-Sections for Liquid Hydrogen and Deuterium for the Design of Cold Neutron Sources", in Proc. Int. Conf. Nuclear Data for Science and Technology, Mito, Japan, 30.5.-3.6.1988, p 477.
- [4] J.U. KOPPEL, J.R. TRIPLET and Y.D. NALIBOFF, "GASKET, a Unified Code for Thermal Neutron Scattering", Report GA-7417 (1966).
- [5] W.D. SEIFFERT, "Messung der Streuquerschnitte von flüssigem und festem Wasserstoff, Deuterium und Deuteriumhydrid für thermische Neutronen", EUR 4455d (1970).
- [6] S.J. TALHOUK, P.M. HARRIS, D. WHITE and R.A. ERICKSON, "Scattering of Thermal Neutrons by Liquid Solutions of Ortho- and Paradeuterium", J. Chem. Phys. 48, 1273, (1968).
- [7] H. WÜRZ, "Untersuchungen zur Neutronenthalisierung an flüssigem Ortho- und Para-Wasserstoff", KFK 1697 (1973).
- [8] P. AGERON, P. DE BEAUCOURT, H.D. HARIG, A. LACAZE and M. LIVOLANT, "Experimental and Theoretical Study of Cold Neutron Sources of Liquid Hydrogen and Liquid Deuterium", Cryogenics 9, 42, (1969).
- [9] W. BERNNAT und J. KEINERT: "Einfluß der kohärenten Neutronenstreuung auf Neutronen-Zuwachsfaktoren kalter D₂-Quellen in D₂O-reflektierten Forschungsreaktoren", Jahrestagung Kerntechnik 90, Nürnberg, 15.-17. Mai 1990.

Evaluation and Validation of Neutron Cross Sections for Liquid Hydrogen and Deuterium for the Design of Cold Neutron Sources

Wolfgang Bernnat

Questions/Answers/Comments

(P. Brewster)

Question: Is there a need for new experimental data?

Answer:

For liquid D₂, we only found measured differential cross sections from Talhouk et. al. and Egelstaff. Double differential cross sections could not be found or were not normalized and complete. For comparison with the theoretical derived double differential cross sections, some more experimental data would be desirable. The measured integral cross sections agree sufficiently good with the theoretical one derived from the liquid kernels.

(W. Bernat)

Comment: The disagreement of experimental energy spectra versus theory at high energies may be caused by resolution. The accuracy of the measured spectrum was not given in detail, so that this may be true. The drop of the measured spectrum from the o-D₂-experiment (SILOETTE) below 0.4 meV may be caused by the chopper.

Neutron Scattering and Transport Properties in Liquid H_2 and D_2 from a Synthetic Model

J. R. Granada
Centro Atómico Bariloche
Argentina

ABSTRACT

In the frame of our Synthetic Model^[1], the interaction of slow neutrons with H_2 and D_2 can be described in a simple way. The main advantage of the model resides in the analytical expressions it produces for the total cross section and the isotropic and anisotropic energy-transfer kernels. In this way, a very fast evaluation of neutron scattering and transport properties in liquid hydrogen and deuterium can be performed, including variation of the concentration in the ortho and para forms.

Results of the application of the Synthetic Model to those systems have been published elsewhere^[2,4], so here we show just a few without going into details already discussed in those publications.

Figures 1 and 2 show our calculated total cross sections for liquid H_2 and D_2 , together with the experimental points of Seiffert^[5].

The slowing down power (per atom) is shown in Figures 3 and 4 for H_2 and D_2 , respectively. The large negative values of $\xi\sigma$ for o- H_2 (Fig. 3) at low energies reflect the importance of upscattering processes through the transition $J = 1 \rightarrow 0$.

The calculated neutron transport mean free path is shown in Figures 5 and 6, where a Maxwellian spectrum has been adopted for the sake of simplicity. The increased leakage in smaller geometries

can then be represented by different Maxwellian temperatures to simulate the corresponding spectrum hardening.

Figure 7 shows our results for the neutron transport mean free path in liquid H₂ as a function of the ortho:para concentration, compared with the calculation due to Würz[6].

Finally, Figure 8 shows our model results for the scalar fluxes corresponding to two concentrations of parahydrogen in liquid H₂ at 20K, together with Maxwellian distributions with a characteristic temperature $T = 37K$.

The main purpose of this comment is to let you know our results and possibilities related to the generation of scattering kernels and group constants for neutronic calculations. As I pointed out above, its ability to produce rapidly the scattering kernels and cross sections for different systems or mixtures of them, makes a Synthetic Model a valuable tool for studies related to the design and optimization of cold neutron sources.

REFERENCES

1. J. R. Granada, Phys. Rev. B 31, 4167 (1985).
2. J. R. Granada, Nucl. Data for Sci. of Technol. (1988 Mito) p. 161.
3. J. R. Granada, V. H. Gillette, M. M. Scaffoni, R. E. Mayer, ICANS '88 (1988 Los Alamos) p. 503.
4. J. R. Granada, V. H. Gillette, R. E. Mayer, Physica B 156, 164 (1989).
5. W. d. Seiffert, Euratom Report EUR-4455d (1970).
6. H. Würz, Report KrK 1697 (1973).

H2 MEAN FREE PATH

⑤

D2 MEAN FREE PATH

⑥

Thermodynamic Performance Tests of the Cold Neutron Source at the Reactor KUR

*Takeshi Kawai, Toru Ebisawa, Masahiko Utsuro,
Yutaka Maeda, Tsunekazu Akiyoshi, Hitoshi Yamaoka,
Sunao Okamoto*

Research Reactor Institute, Kyoto University,
Kumatori-cho, Osaka, 590-04, Japan.

ABSTRACT

This report describes thermodynamic performance tests of the Kyoto University Reactor (KUR) Cold Neutron Source (CNS), which is operated by a closed thermosiphon cooling loop. Close agreement between observed and numerical simulations of the normal operations of the CNS was obtained. Dynamic factors relating to the time-delay caused by the mass transfer in the moderator transfer tube were not considered in those simulations. We can conclude that time-delaying phenomena due to pressure and flow oscillations in the line are estimated to be negligible in our CNS.

The data of TOF spectra showed that the ratio of the fraction

of cold neutrons in the cold moderator to that in the ambient moderator is about 20 where the wavelengths are longer than 6 Å using liquid hydrogen as a moderator.

I. INTRODUCTION

The KUR CNS, with a closed-thermosiphon cooling loop in an inclined moderator transfer tube, has shown a characteristic of self-regulation to the heat load fluctuations. Due to this property, the liquid level in the moderator cell is kept almost constant. The design concept of the closed-thermosiphon cold neutron source and the experimental results of the self-regulation have already been reported⁽¹⁾. We showed in the previous paper⁽²⁾ that the experimental Bode's diagram was in agreement with the numerical predictions of the dynamic equation for the idealized model with a self-regulation.

The present report is concerned with the results of subsequent normal operations of the KUR CNS.

II. RESULTS OF NORMAL OPERATIONS OF KUR-CNS

The important principle in the operation of a reactor CNS is to satisfy the safety criteria for personnel and for the reactor. The details of the safety control system were reported elsewhere⁽³⁾. Fig. 1 shows the safety control system of the CNS facilities.

One of the features in our CNS is that the reactor operation is not prevented by the operational state of CNS. In order not to stop the operation of the reactor even if we found it difficult to operate the refrigerator, two room-temperature helium loops are installed to pour helium gas into the vacuum jacket of the hydrogen cold system for the purpose of removing nuclear heating and preventing the explosion of ozone and hydrogen in case of leakage. Therefore, it is possible to begin operating the refrigerator and store liquid hydrogen in the moderator cell

SAFETY SYSTEM BLOCK DIAGRAM

Fig. 1. Safety control system of the KUR-CNS facilities.

during the operation of the reactor.

Fig. 2 shows the variation of the pressure in the reservoir tank, the temperatures of the helium gas at the inlet and outlet of the condenser, the temperature of the moderator cell and the cold neutron counting rate. The reactor power became 5 MW in about three hours after beginning to operate the refrigerator. The operation of the refrigerator was stopped after about thirteen hours while operating reactor.

Fig. 2. The variation of the pressure in the reservoir tank, the temperature of the moderator cell, the temperatures of the helium gas at the inlet and outlet of the condenser and the cold neutron counting rate during the operation of the cold neutron source under 5 MW power of the reactor.

Fig. 3 shows the numerical simulation of the temperature change of the condenser. The calculating method is described in an appendix.

Fig. 3. Cooldown temperature curve for the condenser.

The temperature of the condenser reaches the liquefying point of hydrogen in about seven hours. Through comparison with a simulation model, the pressure change of the reservoir tank during cooldown is considered to be as follows.

The hydrogen density in the condenser becomes greater when lowering the temperature of the condenser and the pressure decreases gradually. When the temperature of the condenser reaches the liquefying point of hydrogen, hydrogen is liquefied slowly in the condenser and the pressure decreases rapidly.

As the cooldown continues, the liquid front moves down the line to the moderator cell cooling the moderator transfer tube until at last it flows down into the cell. At that time, liquid hydrogen is quickly boiled due to contact with about 100 C aluminum surface of the cell the temperature of which abruptly falls.

As a result, the rate of the upstream gas flow increases steeply and the condenser is heated up and the refrigerant temperature at the outlet of the condenser rises notably for a considerable time duration. However, the temperature rise at

the inlet is small in comparison with that at the outlet.

This phenomenon leads to the apparent increase of the liquefying power of the condenser. The storing rate of liquid hydrogen in the cell agrees almost with the results of the numerical simulation of the pressure of the reservoir tank shown in Fig. 4.

Fig. 4. Calculated pressure variation of the reservoir tank.

In simulating, we consider only the heat loss, the temperature dependent liquefying power of the condenser and heat capacities of the structural materials and hydrogen. The time lag associated with mass transfer through the transfer tube is, hence, estimated to be negligible exclusive of an initial liquid-storing time even under 5 MW power.

The aluminum alloy JIS-A-5052 was used as the structural material of the hydrogen cold system consisting of the condenser, the moderator transfer tube and the moderator cell due to the short life time of the activated isotope and the good transmissivity of cold neutrons. However, the melting point is so low that the maximum temperature reached during the reactor operation is important for the security of the facilities.

Fig. 5 shows the numerical result of the cooldown temperature of the moderator cell. Measured values shown in fig. 2 reach about 100 C due to nuclear heating and an agreement with values of simulation has not been obtained without some additional

cooling power. We have allowed for a cooling power resulting from the mechanism of thermosiphon. This occurs when the temperature of the condenser is decreasing and the temperature difference between the condenser and the moderator cell is increasing.

Fig. 5. Calculated temperature variation of the moderator cell.

The cold neutron counting rate shows a rapid rate of increase and approaches the maximum when liquid hydrogen is not yet filled. After that, its counting rate tends to decrease and becomes constant as liquid hydrogen flows down in the cell. This is because the volume of the moderator cell is 4 litres and larger than the volume required for the hydrogen cold moderator.

Fig. 6 shows the cold neutron spectra measured with a TOF apparatus shown in fig. 7⁽⁴⁾.

Fig. 6.

Cold neutron spectra measured with the supermirror set at an angle of $1/121$ rad in cases of CNS-on and CNS-off.

Fig. 7. Apparatus arrangement for measurement of cold neutron spectra.

A supermirror deflector is used in order to pick up cold neutrons and remove epithermal neutrons and γ -rays from the reactor core. The ratio of the fraction of cold neutrons in the cold moderator (CNS on) to that in the ambient moderator (CNS off) is about 20 for wavelengths longer than 6 Å using liquid hydrogen as a moderator. This value shows a satisfactory agreement with a numerical prediction⁽⁵⁾.

III. CONCLUSIONS

KUR-CNS is so designed and constructed as to have a self-regulating characteristic. Measured results of the thermodynamic normal operation of CNS agreed approximately with the calculated results without taking account of the dynamical factors resulting from the mass transfer in the moderator transfer tube. The effect of pressure and flow oscillations leading to the time-lag phenomena in the line is, hence, estimated to be negligible in our CNS.

The gain factor for cold neutrons showed a satisfactory result.

IV. ACKNOWLEDGEMENTS

KUR-CNS was manufactured by Nihon-Sanso Comp. Ltd.. The authors wish to express their gratitude to Me'ssrs Tameyoshi TASHIRO, Shoji SAKAKIBARA, Minoru KATADA and Takashi FUKANO of the comp. for useful discussions concerning the structural design of CNS.

V. REFERENCES

1. T. Kawai et al., Nucl. Instrum. Methods, A276, 408 (1989).
2. T. Kawai et al., Nucl. Instrum. Methods, A285, 520 (1989).
3. T. Kawai et al., Proc. Int. Conf. on Neutron Physics, Kiev, USSR, Sept. 14-16, 1987, ed. B.D. Kuzyminov, vol.4, 79 (1988).
4. T. Ebisawa et al., Ann. Rep. Res. Reactor Inst. Kyoto Univ., 22, 1 (1989)
5. K. Okumura and M. Utsuro, Private communications.
6. T. Kawai et al., KURRI-TR-317, (1989) (in Japanese).

VI. APPENDIX

The method to calculate the cooldown time for a heat-insulated cryogenic system is through a temperature jump method. According to the model, the cooldown time is expressed as the ratio of the heat removed from the system to the rate of its removal, i.e. cooling power. The model assumes that a stationary value is rapidly established and that axial temperature gradients arising in the moderator transfer tube and conduit can be neglected under cooldown.

The cool down time of the condenser can, hence, be found from the following heat balance equation:

$$\Delta t = \frac{\sum_{i=1}^n W_i C_{p,i} \Delta T}{Q_R - Q_{HL}} \quad (1)$$

where Δt [s] is the time it takes for the system temperature to

drop by $\Delta T[K]$, $W_i C_{p,i} \Delta T [J/K]$ is the i -th material heat removed ($W[g]$ is a weight and $C_p [J/g \cdot K]$ is a heat capacity) and $Q_R [W]$ and $Q_{HL} [W]$ are the time dependent cooling power of the refrigerator and the heat loss with nuclear heating⁽⁶⁾.

For treating hydrogen cool down, we introduce the heat $\Delta Q [J]$ required for lowering the temperature of hydrogen transferred from the reservoir tank to the hydrogen cold system by ΔT . The cooldown time Δt of hydrogen can be written as:

$$\Delta t = \frac{\sum_i^n W_i C_{p,i} \Delta T + \Delta Q}{Q_R - Q_{HL}} \quad (2)$$

The mass flow $\Delta G [g]$ of hydrogen from the reservoir to the hydrogen cold system may be written in terms of the volume $V_H [cm^3]$ of the hydrogen cold system and hydrogen density $\rho_H [g/cm^3]$ initially within the system and ρ_H' at the time $t + \Delta t$:

$$\Delta G = (\rho_H' [P', T'] - \rho_H [P, T]) V_H \quad (3)$$

where the parentheses denote the functional form of ρ_H and we assume the equation of state for an ideal gas. The heat ΔQ is obtained in terms of ΔG and the enthalpy of hydrogen, $H [J/g]$, as:

$$\Delta Q = G_R H_R + G_H H_i - \{ (G_R - \Delta G) H_R + (G_R + \Delta G) H_f \} \quad (4)$$

where subscripts R, H stand for the reservoir tank and the hydrogen cold system. Subscripts i and f denote the initial and final time. $G [g]$ denotes hydrogen mass.

The pressure of the reservoir at the time, $t + \Delta t$, is obtained from the following mass balance equations:

$$\Delta G = (\rho_H [P_i, T_R] - \rho_H [P_f, T_R]) V_R = (\rho_H [P_f, T - \Delta T] - \rho_H [P_i, T]) V_H \quad (5)$$

With the hydrogen mass w_c [g/s] liquefied per unit time in the condenser, the time required to store liquid hydrogen, G_M [g] in the moderator cell is obtained as follows:

$$\Delta t = G_M / w_c \quad (6)$$

The w_c is expressed in terms of the enthalpy of the saturated hydrogen vapor, H_u [J/g], and the latent heat of hydrogen, ΔH [J/g]:

$$w_c = (Q_R - Q_{HL}) / (H_R - H_u + \Delta H) \quad (7)$$

For the heating up process, the procedure to calculate is as follows:

$$\Delta t = (Q_f - Q_i) / Q_{HL} \quad (8)$$

where $Q[w]$ is the heat of the hydrogen. The heat of the hydrogen, in the case when liquid hydrogen is still stored in the moderator cell, is given in terms of the volume ratio of liquid hydrogen in the moderator cell at time t , x_L [%], as:

$$Q = V_M \rho_{HL} H_L x_L / 100 + \{ V_M (1 - x_L / 100) + V_T + V_C \} \rho_{Hu} H_u + V_R \rho_{HR} H_R \quad (9)$$

where subscripts M, T, C denote the moderator cell, the moderator transfer tube and the condenser, and subscripts L and V denote the liquid and vapor of hydrogen in a saturated state. Similarly, the heat when the chamber is empty is given as:

$$Q = (V_M + V_T + V_C) \rho_H [P_i, T_i] H_i + V_R \rho_H [P_i, T_R] H_R \quad (10)$$

Thermodynamic Performance Tests of the Cold Neutron Source at the Reactor KUR

Takeshi Kawai

Questions/Answers/Comments

(B. Farnoux)

Question:

Do you have measurements of the neutron intensity variation when the refrigerator is stopped?

Answer:

Yes, we have measured this already. The cold neutron flux is evaluated to be 2.7×10^8 [n/cm²-s-steradian] in the range longer than 6 Å when the liquid hydrogen has evaporated.

A Practical Approach to the Polymerization of Liquid Methane in a Cold Moderator

A. T Lucas
Rutherford-Appleton Laboratory
Chilton, Didcot, oxon
UNITED KINGDOM

ABSTRACT

The ISIS liquid methane moderator is now running regularly with pulsed neutrons from a 750 MeV proton beam at 100 μ A intensity on to a depleted uranium target. Polymerization of the methane produces an oily contamination which threatens to cause blockages in the cryogenic system when still higher intensities are attained. This paper outlines some methods considered to address the problem and goes on to describe in some detail an on-line method of recharging the cryogenic system with fresh liquid methane without interrupting its operation.

I. INTRODUCTION

Polymerization of liquid methane occurs when it is subjected to ionizing radiation. This results in the production of long chain molecules, which in the early stages take the form of oils of the paraffin family. Successive radiation would cause more complex cross linking, eventually leading to the formation of solids. The oil is soluble in liquid methane to some extent but it appears likely that some quantity is carried in the liquid methane as a mixture. The precise nature of the fluid is unknown in the absence of an examination in liquid state. At a flow rate of 0.5 l/sec, together with inherent bends in the cryogenic circuit, the presence of these oils represents a potentially serious flow problem.

II. POSSIBLE SOLUTIONS

Since little was known of the extent of the problem during the design stages of the ISIS moderator, the only recourse was to specify in-line filters with a pore size of 13 microns. The pressure drop across each filter was constantly monitored and when it became excessive, the flow was switched to a second filter. It soon proved necessary to increase the pore size to achieve a useful operating period from each filter element. As beam intensity from ISIS has been increased, the quantity and viscosity of oils trapped in the filters has increased accordingly. It is clear that unless the problem is addressed, blockages will occur with higher beam intensities. Filters are currently removed and saturated with the oils which carry a radiation dose/rate of about 200 $\mu\text{Sv/hr}$ suggesting a potential contamination hazard.

A number of possible solutions to the problem have been examined in some detail:

1. Centrifuging—A centrifuge to effect separation of the liquids using the resulting tangential velocity to skim off the heavier oily compounds is a possibility since a density ratio of about 2:1 exists between the two. However, it is impossible to sensibly calculate the efficiency of such a device considering the high flowthrough rate of 0.5 L/sec. A development program would be required, requiring either a cold test rig capable of operating with the true liquids, or the use of an on-line moderator system. The latter would clearly involve some element of risk, the extent of which and its justification would have to be weighed against its anticipated success.
2. Liquid/vapor separation—Liquid methane could be vaporized by either raising its temperature, or reducing its pressure. The liquid polymers could then be isolated in a separator and the methane restored to liquid. Again a development program to design either a high efficiency contra flow heat exchanger, or a cryogenic pump to produce a pressure ratio of 16:1 would be required.
3. Other methods—Sophisticated techniques such as hydrocracking have been postulated but it appears that such methods are too complicated and costly for a system of this size.

Note: Attempts were made to enlist specialist help in gaining a better understanding of the chemical processes involved, but this would require a fairly detailed research program to be of any real value.

4. Solvents—The possibility of regular flushing with a solvent was considered. However, apart from the loss of time in the warming up and recooling of the system, it would be very difficult, if not impossible, to remove such solvents from a cryogenic system with its bends and restrictions. Removal by evaporation would destroy the object of the exercise since the polymers would then be left behind in the system.
5. Liquid Exchange—The remaining solution considered in this paper is to flush out as much as possible of the liquid methane charge together with its impurities using a fresh charge of liquid methane. This has the great advantage of not requiring any warming up of the cryogenic system, a definite removal of a large proportion of the contaminants, and little "if any" interruption to the operation of the moderator.

The remainder of this paper describes the practicality of such a system and the engineering significance of integrating it into an existing moderator loop.

III. PRINCIPLES OF OPERATION

A simplified flow diagram is shown in Fig. 1. During normal operation the diverter valve V4 would convey liquid from the refrigerator to circulator 2 or 3, the inlet from the condenser being closed off. The return route would be through Filter 1 or 2 and then through the coil of the condenser back to the refrigerator. The main control heater on the return leg would operate in response to temperature sensor T4 which is the temperature most representative of that in the moderator and circulator 1 would be switched off and isolated by Valves V1 and V2.

To accumulate a fresh charge of liquid, methane gas at a controlled pressure would be admitted into the condenser main vessel. According to the available refrigeration watts this gas would be cooled and subsequently liquified. Control of the overall system is described in Section IV (see Fig. 1A).

In order to make a liquid change V4 is changed over, and circulator 1 started with Valves V1 and V2 open. With V9 and V10 closed, V16 and V13 are opened to allow Circulator 2 or 3 to pump liquid from the condenser main vessel. The old liquid will not be displaced into internal precooled waste tank until a low level sensor in the condenser is activated. This operation should take less than one minute, after which the valves would be reset for normal operation and Circulator 1 stopped and valved off. During liquid exchange, a quantity of the old liquid would be circulated in a small loop around the refrigerator head in order to keep it in a cold standby state (see Fig. 1B). The control heater would be activated by Sensor T1

during the operation of Circulator 1. The waste tank heater would then be powered, once isolated, to boil off the old liquid. The polymers would remain behind in the waste tank, but it would be possible to flush this out periodically through a bottom drain using a solvent.

The normal volume inventory of liquid in the circuit is about 20 L. Of this, about 3-4 liters would remain in the small loop, there would also be some mixing of new and old liquids. However, about 75-80% of the liquid would be renewed, and the remainder could be further diluted by a repeat operation some hours later. Clearly, the frequency of liquid changes would be geared to the available surplus refrigerator watts, but this should prove more than adequate to keep the system operational.

IV. CONTROL OF SYSTEM

With reference to Fig. 1, the moderator is normally operated at 100K with a liquid flow of 0.5 l/sec at 4 bar absolute pressure. This represents about 20K of sub cooling to avoid any possibility of boiling in the moderator, with reference to ICAN-IX Proceedings, p 305, the maximum estimated heat load of the ISIS methane moderator for a proton beam intensity of 200 μ A, is 780 W. The refrigerator output at 100K is 1000 W leaving a useful 220 W surplus. The LANSCE proposed moderator is designed around a later version of a similar refrigerator, delivering 1500 w at 100K. However, since two moderators in tandem are envisioned, the surplus would be somewhat less for a proton beam intensity of 200 μ A. With the beam off, however, the absence of neutronic heating would add about 625 W to the surplus refrigeration on the ISIS system, and well over 1 kw on the LANSCE system. Both systems have a liquid capacity of around 20 L, and a full charge from gas at NTP would be produced in about 11 hours at 220 W, 3 hours at 800 W and 2 hours at 1200 W.

Since tight control of the moderator temperature is of paramount importance, the contribution of refrigerator power given up to the condensor would have to be controlled to allow a working margin for the temperature control system. This would be achieved by a by-pass valve across the condensor operating automatically if heater power should fall below a minimum of say 40 W (see Fig. 1C).

During liquid exchange, temperature control of the closed loop circuit would be from sensor T1.

V. PRACTICAL LAYOUT

Figure 2 shows the annular configured condensor suspended from the top of the transfer vessel. This makes for the best assembly of the valves and places the condensor at the correct height with respect to the circulators and refrigerator. Also this arrangement keeps the quantity of liquid in the small loop to a minimum allowing a larger proportion of liquid to be replaced. The dump tank is suspended below, with good thermal connections to the condensor allowing it to precool in readiness to accept liquid without

violent boiling occurring. An electrical heater on the dump tank enables liquid to be washed out with a solvent periodically through a bottom drain pipe fitted with an outset valve.

VI. CONCLUSIONS

This proposal has a clear advantage of not changing a working and proven system. The new components are used only when required so that normal operation should not in any way be affected. Also, being a "total loss" system, its efficiency over continuous separation methods is more predictable.

As already pointed out, some old contaminated liquid will remain in the system and some mixing of the old and new will take place. However, the overall effect will be to replace a large proportion of the liquid and further exchanges are governed only by the refrigeration capacity available. It is envisioned that the exchange procedure will eventually be automated by means of a programmable controller.

Appendices

Appendix A

Bibliography of Cold Neutron Sources: Design and Performance

Peter M. Brewster

This bibliography lists reports and journal articles that describe the design and performance of cold-neutron sources. The list is not comprehensive; there are only a few reports describing accelerator-based cold sources, ultracold neutron sources, or materials properties for cold sources. Several papers that describe neutron scattering cross sections of hydrogen are included.

Most of the information is taken from DOE ENERGY and INIS (International Nuclear Information System) computer-literature searches. The INSPEC 88 entry is another database-generated bibliography.

The bibliography is listed in alphabetical order by author. It is also referenced in the index at the end of the bibliography.

The contents of a typical entry consist of

- Last name of first author
- Title
- Authors' names
- Laboratory
- Reference publication or report number
- Language, if not English
- Work Location
- Abstract, if available

Thanks are extended to Wendy Hawley for preparing this text.

Comments should be addressed to P. M. Brewster, AECL Research Company, Chalk River, Ontario, K0J 1J0.

AGERON

EXPERIMENTAL AND THEORETICAL STUDY OF COLD NEUTRON SOURCES OF LIQUID HYDROGEN AND LIQUID DEUTERIUM

Ageron, P.; De Beaucourt, Ph.; Harig, H.D.; Lacaze, A.; Livolant, M.
Cryogenics 9, 42-50 (1969)

Liquid hydrogen moderators are installed in the 100 kW SILOETTE reactor at Grenoble. Neutron spectra emerging from the beam tube, for various moderator chamber designs, are reported. Annular layers of H₂ are used: 0.7, 1.5 and 3 cm thick, in an 18 cm diameter cylinder, with a few different ortho to para ratios. The D₂ cylinders are 18 and 38 cm in diameter, with an optional re-entrant cavity along the beam direction. Multigroup calculations using approximate scattering kernels are reported. Reasonable agreement is found with the H₂ measurements. Discrepancies with the D₂ data are attributed to the scattering kernel chosen and to flux gradients in the surrounding D₂O tank. (P.M.B.)

COLD NEUTRON SOURCE OF THE FRENCH--GERMAN HIGH FLUX REACTOR IN GRENOBLE

Ageron, P.; Verdier, J.; Ewald, R.; Harig, H.D.
CEA, Grenoble, France
Energ. Nucl. (Paris) 13: No. 1, 15-21 (1971 Jan-Feb).
Language: French

COLD NEUTRON SOURCES FOR THE HIGH-FLUX REACTOR AT GRENOBLE

Ageron, P.; Verdier, J.; Ewald, R.; Harig, H.D.
CEN, Grenoble, France
Atomwirt., Atomtech. 16: 125-9 (1971 Mar.).
Language: German

HIGH FLUX FRANCO--GERMAN REACTOR. THE COLD NEUTRON SOURCE OF THE HIGH FLUX REACTOR

Ageron, P.; Astruc, J.M.; Geipel, H.; Verdier, J.
Institut Max von Laue--Paul Langevin, Grenoble, France
Bull. Inform. Sci. Tech. (Paris) No. 166: 17-22 (1972 Jan.).
Language: French
Translation ORNL-tr-5085

COLD AND ULTRA-COLD NEUTRONS: A TEST FACILITY FOR CRYOGENIC ENGINEERING

Ageron, P. (ILL, Grenoble, France); Astruc, J.M.; Lacaze, A.; Verdier, J.;
Mendelssohn, K. (ed.)
Proceedings of the Fifth International Cryogenic Engineering Conference, Kyoto, Japan, May 1974.
IPC Science and Technology Press Ltd., Guildford, Eng., 458-460, (1974).

The industrial applications of cryogenics are often held back by doubts about reliability. This paper describes the Grenoble Cold Neutron Source, with which an operating rate of 99.4% has been achieved, and which hence augurs well for the future of industrial plants working near 4 K.

PRELIMINARY MEASUREMENTS OF THE PERFORMANCE OF THE SOURCE OF ULTRA-COLD AND VERY COLD NEUTRONS AT ILL

Ageron, P.; Hetzelt, M.; Mampe, W. (Institut Max von Laue - Paul Langevin, 38 - Grenoble (France)); Golub, R.; Pendelbury, M.; Smith, K. (Sussex Univ., Brighton (UK)); Robson, J. (McGill Univ., Montreal, Quebec (Canada))

Neutron Inelastic Scattering 1977. Vol. 1

International symposium on neutron inelastic scattering Vienna, Austria 1977 Oct. 17

Publ: IAEA, STI/PUB/468 p. 53-65 (1978)

The ultra-cold (UCN) and very cold neutron (VCN) source, put into operation in 1977 April at the high-flux reactor of the Institut Laue-Langevin (ILL), provides a beam of neutrons with velocities lower than 50 ms^{-1} (wavelength longer than $80 \text{ \AA}$) which do not exist in the other beams. A description is given of the different parts of the source: the in-pile guide, in an inclined beam tube, with a room-temperature water converter in a flux of $6 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$, the curved guide inside an external shield, and the distribution system to three experimental sites. Theoretical neutron spectra of such a source are indicated. The measurements of the flux and of the spectra are made by means of four different methods: conventional time-of-flight over the whole range, time-of-flight with a pre-selection of UCN, gravity spectrometer, and UCN storage in a 'bottle', for the UCN range. The total flux in the beam is $2 \times 10^5 \text{ n cm}^{-2} \text{ s}^{-1}$ with the maximum of the spectra at 60 ms^{-1} . The total UCN flux (velocity lower than 6.2 ms^{-1}) is, after correction of the TOF and 'bottle' measurements, evaluated at about $300 \text{ n cm}^{-2} \text{ s}^{-1}$.

ILL FACILITIES FOR FUNDAMENTAL PHYSICS EXPERIMENTS

Ageron, P.; Mampe, W.

J. Phys. (Paris), Colloq. 45(C-3) p. 279-284 (1984 Mar.)

A presentation is given of the characteristics of thermal, cold, very cold and ultracold neutron beams available for fundamental physics experiments at the ILL high flux reactor.

SPECIAL NEUTRON SOURCES

Ageron, P.

Neutron Scattering in the 'Nineties. Proceedings of a IAEA-CN-46/16

Conference Organized by the IAEA in Co-operation with the Juelich Nuclear Research Centre and Held in Juelich, p. 135-156 (1985).

Publ: IAEA STI/pub/694

In some specific energy ranges of interest the neutron intensities are so low in conventional research reactors that they cannot be used for experiments which would be possible only at these energies. Special devices have been developed in order to enhance locally the intensity of such neutrons. They include, for hot neutrons, moderators of limited sizes at high temperature (1500 to 2000K) and for cold, very cold, and ultra-cold neutrons, moderators also of limited size at a low temperature (around 20K) which increase the brightness of the source in the reactor (flux per unit of solid angle), and neutron guides with total reflection, which increase the solid angle of collection. Thus, combining the two, a large increase of the total flux available to the user can be obtained. This paper summarizes some attempts to optimize such moderators - size, shape, temperature, nature of material - while taking into account the technical constraints (nuclear heating, material strength, radiation damage, safety consideration, etc.). Despite this optimization the net experimental results are far below the theoretical value which can be expected, especially in the field of UCNs, which are very sensitive to tiny defects. The fact that neutron lifetime in a material bottle has been increased considerably allows one to expect similar improvements in the production and guidance of UCNs.

**COLD AND ULTRA COLD NEUTRON BEAMS FOR FUNDAMENTAL PHYSICS
RESEARCH AT THE INSTITUTE LAUE-LANGEVIN**

Ageron, P.; Mampe, W.; Greene, G.L. (ed.)

Institute Laue-Langevin, Grenoble, France

National Bureau of Standards, Washington, DC (USA)

Workshop on the investigation of fundamental interactions with cold neutrons,

Gaithersburg, MD, USA 1985 Nov. 14

NBS/SP-711; CONF-8511137, p. 16-24 (1986 Feb.)

All experiments discussed at this workshop need intense beams of low-energy neutrons with low gamma ray and fast-neutron backgrounds. The High Flux Reactor of the ILL, Grenoble, offers, in connection with the integrated cold and ultra-cold sources, a large variety of those facilities. The beams, transported in neutron guides, cover the whole wavelength range from one Angstrom to several thousand Angstroms. 9 refs.; 8 figs.

ALTAREV

**UNIVERSAL LIQUID-HYDROGEN SOURCE OF POLARIZED COLD AND
ULTRACOLD NEUTRONS AT THE WWER-M LIYAF REACTOR**

Altarev, I.S.; Borovikova, N.B.; Bulkin, A.P. (and others).

PIS'MA ZH. EHKSP. TEOR. FIZ. V. 44(6) p. 269-272 (1986 Sept. 25).

For English translation, see the Journal JETP letters (USA) 44, p. 344-348 (1986)

Record values of polarized cold-neutron flux density and intensity ($3 \times 10^{10} \text{ s}^{-1}$ and $6 \times 10^8 \text{ s}^{-1} \text{ cm}^{-2}$), as well as ultracold-neutron intensity ($5 \times 10^5 \text{ s}^{-1}$) with $6 \times 10^3 \text{ s}^{-1} \text{ cm}^{-1}$ flux density for $V_x, V_y, V_z < 7.8 \text{ m/s}$ velocity interval are obtained at a medium power reactor. The neutron beam polarization degree is $90 \pm 5\%$. Investigations into the ultracold- and cold-neutron yield for deuterium and hydrogen-deuterium mixtures are carried out.

ANTONOV

ON THE USE OF LIQUID HYDROGEN AS A COLD NEUTRON SOURCE

Antonov, A.V.; Vo Dak Bang; Isakov, A.I.; Merkul'ev, YU. A.

Neutron Physics

Proceedings of the All-Union Conference, Kiev PT. 1 P. 119-123, 1971 May 24-28, Naukova Dumka, 1972.

Laanguage: Russian

AZMY

**A DIFFUSION THEORY MODEL FOR OPTIMIZATION CALCULATIONS OF COLD
NEUTRON SOURCES**

Azmy, Y.Y.

Oak Ridge National Lab., TN (USA)

Joint meeting of the American Nuclear Society and the Atomic Industrial Forum

Los Angeles, CA, USA 1987 Nov. 15, CONF-871101-7

Trans. ANS 55, 343-4 (1987 Nov)

This summary describes a simple two-group diffusion model of an infinite slab, liquid deuterium (LD_2) cold source. The simplicity of the model permits us to obtain an analytical solution from which we can deduce the reason for the optimum thickness based solely on diffusion type phenomena. Also, a second more sophisticated model is described, and the results compared to a deterministic transport calculation. The good (particularly qualitative) agreement between the results suggests that diffusion theory methods can be used in parametric and optimization studies in order to avoid the generally more expensive transport calculations.

GEOMETRICAL SHAPE OPTIMIZATION OF A COLD NEUTRON SOURCE USING ARTIFICIAL INTELLIGENCE STRATEGIES

Azmy, Y.Y.

ANS Proc. on Topical Meeting on Advances in Nuclear Engineering Computation and Radiation Shielding, Santa Fe New Mexico, 67.1-67.12, (1989 April)

A new approach is developed for optimizing the geometrical shape of a cold neutron source to maximize its cold-neutron-outward leakage. An analogy is drawn between the shape optimization problem and a state-space search, which is the fundamental problem in Artificial Intelligence applications. The new optimization concept is implemented in the computer code DAIT in which the physical model is represented by a two group, r-z geometry nodal diffusion method, and the state-space search is conducted via the Nearest Neighbor algorithm. The accuracy of the nodal diffusion method solution is established on meshes of interest, and is shown to behave qualitatively the same as transport theory solutions. The dependence of the optimum shape and its value on several physics and search parameters is examined via numerical experimentation.

BASU

COLD NEUTRON SOURCE FOR THE DHARVA REACTOR: OPTIMIZATION CALCULATIONS

Basu, S.; Dasannacharya, B.A.

Bhabha Atomic Research Centre, India

Nucl. Inst. Meth B18, 311-315 (1987)

A 15-cm-diameter liquid methane cylinder at 110 K is predicted to have an optimum height of 2.0 cm, for the flux conditions of the DHARVA reactor.

BAUER

NEUTRON BEAM GUIDE AND EXTERNAL NEUTRON LABORATORY OF A COLD NEUTRON SOURCE

Bauer, G.; Joswig, G.; Schelten, J.; Schmatz, W.

Inst. fuer Festkoerperforschung, Juelich, Ger.

Kerntechnik 14: No. 1, 9-12 (1972 Jan.).

Straight neutron-beam guides are used inside the FRJ-2 reactor hall. In the external laboratory a curved neutron guide and a straight guide split the incident beam. Bismuth crystal filters, at low temperature, are used to alternate gamma rays and fast neutrons. The neutron guides, beam shutters and shielding are briefly described. (P.M.B.)

BEAM QUALITY AND OPERATIONAL BEHAVIOUR OF THE COLD NEUTRON SOURCE WITH NEUTRON CONDUCTORS AT THE RESEARCH REACTOR FRJ-2 (DIDO)

Bauer, G.; Zinken, A.; Tholen, A.

Juel-1075-FF. 56 p. (1974 May)

NOTE: 23 refs.; 4 tabs.; 21 figs.

Language: German

BERNNAT

EVALUATION OF NEUTRON CROSS SECTIONS FOR LIQUID HYDROGEN AND DEUTERIUM FOR THE DESIGN OF COLD NEUTRON SOURCES

Bernnat, W.; Emendorfen, D.; Keinert, J.; Mattes, M.

Proc. Int. Conf. Nuclear Data for Science and Technology p. 477 (1988 May 30 - June 3) Mito, Japan

Cross sections for slow-neutron scattering from H_2 and D_2 have been calculated taking into account the liquid state. The ability of the model is demonstrated by comparison with experimental results for differential and total cross-sections. For applications the scattering law $S(\alpha, \beta)$ has been prepared in the ENDF-5-format for different temperatures as a basis for the generation of scattering matrices. From calculations of neutron spectra with different scattering models it turns out that the gain factor for cold neutrons is sensitive to the liquid state. Below 1 meV the frequently used Young-Koppel model for a molecular H_2 -gas overestimates the gain factor by about 50%.

BUCHHOLZ

BERLIN EXPERIMENTAL REACTOR (BER) OF HMI

Buchholz H. Von

Hans-Meitner-Institut, Berlin

Atomwirtsch, Atomtech 29, 258-260 (1984)

Jointly with Interatom, HMI designed a swimming pool reactor, BER II, with 5MW power. BER II was commissioned in late 1973. The continuing need for measuring stations for neutron scattering now necessitates an expansion of BER II with the objective of greatly increasing the neutron flux densities at the beamholes. In addition, the installation of a cold-neutron source is being planned.

PUBLIC NOTICE CONCERNING AN APPLICATION FILED FOR PERMISSION TO INSTALL AND OPERATE A COLD NEUTRON SOURCE IN THE BER-2 RESEARCH REACTOR OF HAHN-MEITNER

Institute, Berlin. As of 1987 February 25.

Bundesanzeiger (Germany, Federal Republic of) v 39:45, p. 2278, 1987 March 6.

Language: German

Note: Published in summary form only; see above.

BUTTERWORTH

THE PRODUCTION OF INTENSE COLD NEUTRON BEAMS

Butterworth, I.; Egelstaff, P.A.; London, H.; Webb, F.J.

AERE Harwell

Phil. Mag. 2, 917-27 (1957 July).

The moderation of pile neutrons to very low energies has been investigated. Liquid hydrogen, liquid hydrogen deuteride and methane at 20°K were found to be effective moderators. After an examination of the safety aspects, a volume of liquid hydrogen was maintained at the centre of a reactor, and the velocity spectrum of neutrons scattered from it was measured. Appreciable moderation of neutrons to very low energies was observed. By this method it is practicable to increase considerably the flux of cold neutrons in a beam. Thus, in the present experiment the flux of 10 Å wavelength was increased by a factor of 25.

NOTE: This paper describes the first reactor based cold source: the liquid hydrogen chamber in BEPO.

CARNEIRO

COLLECTIVE EXCITATIONS IN LIQUID HYDROGEN OBSERVED BY COHERENT NEUTRON SCATTERING

Carneiro, K.; Nielsen, M.; McTague, J.P.

RISO

Phys. Rev. Lett 30, 481-485 (1973)

Coherent scattering of neutrons by liquid parahydrogen shows the existence of well-defined collective excitations in this liquid. Qualitative similarity with the scattering from liquid helium is found.

CARTER

STUDY OF COLD NEUTRON SPECTRA EMERGING FROM SOURCES OF LIQUID HYDROGEN AND DEUTERIUM AND A MONTE CARLO METHOD FOR OPTIMISATION

Carter, P.; Jones, D.M.

Atomic Energy Research Establishment, Harwell, Eng.

J. Nucl. Energy 26: No. 5, 237-49 (1972 May).

Measurements of the moderating efficiency of cold-neutron sources (with simple transmission geometry) containing liquid hydrogen, liquid deuterium and mixtures of the two are described. A Monte Carlo method of calculating the cold-neutron outputs has been devised and calculations based on the theoretical cross sections of Young and Koppel satisfactorily reproduce the experimental spectrum shapes, optimum depths of moderator and cold-neutron outputs. This method is quite adequate for optimising the design of future cold sources ($\pm 20\%$). It was found that the calculated deuterium cross sections must be modified for wavelengths beyond 5 Å so that the total cross sections correspond to the measured values of Seiffert (adjusted to the operating temperature).

CALCULATIONS OF THE PERFORMANCE OF VARIOUS 'COLD NEUTRON SOURCES' FOR A HIGH FLUX BEAM REACTOR

Carter, P.; Hey, P.D.; Newport, R.W.; Sterling, G.C.
AERE, Harwell and Rutherford Laboratory, Chilton
RL-74-093, p. 34 (1974)

The performance of liquid hydrogen and deuterium cold-neutron sources suitable for installation in a proposed Harwell high-flux beam reactor have been investigated for wavelengths up to 15 Å, using Monte Carlo calculations. The effects of various limitations such as heat transfer have been taken into account. The results indicate that large deuterium sources are likely to be the most effective by more than a factor of two when compared with hydrogen sources. 4 tab.; 15 fig.; 14 ref.

THE NATIONAL BUREAU OF STANDARDS COLD NEUTRON RESEARCH FACILITY

Carter, R.S., U.S. NBS
Trans. ANS 55, 188 (1987 Nov)

A 35 kg cylinder of D₂O ice (35 cm diameter 33 cm long) at 30 K has been installed in a re-entrant cavity in the NBS reactor.

COCKING

BEAM INTENSITY MEASUREMENTS ON THE DIDO COLD NEUTRON APPARATUS

Cocking, S.J.; Webb, F.J.
Atomic Energy Research Establishment, Harwell (England)
Primary Report No.: AERE-R-5168, p. 24 (1967)

The inpile section of the liquid hydrogen loop in DIDO was replaced during 1965. This report gives the results of beam measurements over a range of neutron wavelengths made on the earlier loop and its replacement. The flux gain obtained with use of the liquid hydrogen moderator was 6 for 4.2 Å neutrons increasing to 11 for 8 Å neutrons. Despite modification to the shape and volume of the moderator chamber these gain figures differ little between the two loops. Attempts were made to fit the observed spectra and gain factors using both single and two component Maxwellian spectra. The observed flux gain factor for 4.1 Å neutrons on cooling the polycrystalline beryllium filters, with liquid nitrogen, was 3.9. The overall fluxes with the new equipment are higher than those obtained earlier; the improvement ranges from 50% at 4.1 Å to more than 100% at longer wavelengths.

DAHLBORG

'HYBRID' TIME-OF-FLIGHT SPECTROMETER FOR COLD NEUTRONS

Dahlborg, U.; Groenros, M.; Karlsson, L.E.; Olsson, L.G.; Johnsson, T.; Noreus, D.; Larsson, K.E.
(Kungliga Tekniska Hogskolan, Stockholm (Sweden) Inst. of Reactorphysics)
Nucl. Instrum. Methods (Netherlands) v 171:1. p. 181-183 (1980 April)

A new cold-neutron spectrometer has been installed at the R2 reactor at Studsvik. The energy resolution of the spectrometer is in the range 0.09-0.4 meV.

DIMIC

COLD NEUTRON SOURCE EFFICIENCY IN A TANGENTIAL BEAM HOLE

Dimic, V.; Petkovsek, J.

Inst. Jozef Stefan, Ljubljana, Yugoslavia

Nucl. Instrum. Methods 96: No. 2, 285-8 (1971).

Using a room temperature methyl alcohol moderator, the cold-neutron beam intensity has been measured for differently shaped moderator chambers at different positions in a 15 cm diameter tangential beam hole of the reactor Triga Mark II measurements have been performed at ambient temperatures. It has been found that the most favourable configuration for a moderator is a "black body" scatterer with a gain factor of 19 relative to the empty beam hole and of 1.7 relative to the 15 cm long graphite slab.

IMPROVED VERSION OF THE METHANE COLD NEUTRON SOURCE

Dimic, V.

Univ. of Ljubljana, Yugoslavia

Nucl. Instrum. Methods 107: No. 2, 405-406 (1973).

A new version of a cold-neutron source facility, using methane as a moderator, has been installed recently in one of the tangential beam tubes of the reactor TRIGA Mark II at the Institute "Jozef Stefan", Ljubljana. The construction and performance of the facility are described.

DOOSE

BEAM TUBE EQUIPMENT FOR THE FRJ-2 (DIDO) COLD NEUTRON SOURCE

Doose, C.

Kernforschungsanlage, Juelich F.R. Germany

Primary Report No.: AERE-Trans-1043, p. 22 (1965)

Note: Translated by J.B. Sykes (Atomic Energy Research Establishment, Harwell, Eng.), from an internal report

CONSTRUCTION AND OPERATION OF THE COLD NEUTRON SOURCE AT THE REACTOR FRJ-2

Doose, C.; Tholen, A.

Kernforschungsanlage, Juelich, Ger.

Kerntechnik 13: No. 12, 539-49 (1971 Dec.).

The safety requirements are listed. The design of the cold-source-plug assembly is discussed. The cooling circuits and safety devices are described. (P.M.B.)

PLANNING AND DEVELOPMENT OF THE COLD NEUTRON SOURCE AT THE REACTOR FRJ-2

Doose, C.

Kernforschungsanlage, Juelich, Ger.

Kerntechnik 13: No. 12, 528-33 (1971 Dec.).

COLD NEUTRON SOURCE IN JUELICH

Doose, C.; Preussner, A.; Stelzer, F.; Stiller, H.; Tholen, A.
Kernforschungsanlage, Juelich, Ger.
Cryogenics 11: 107-13 (1971 April).

An overview of the design, operation and controls of the cold-source in FRJ-2 is given. Details of the heat load and performance of the thermosyphon system are provided. The relationship between the head load and hydrogen flow rate, for various design parameters, is given. (P.M.B.)

ENGINEERING ASPECTS OF THE COLD NEUTRON SOURCE AT THE REACTOR DIDO

Doose, C.; Stelzer, F.; Stiller, H.; Tholen, A.
Kernforschungsanlage, Juelich, Ger.
Symposium on irradiation facilities for research reactors
Publ: International Atomic Energy Agency, Vienna, STI/PUB/316 p. 235-246 (1973)

EGELSTAFF

ON THE EVALUATION OF THE THERMAL NEUTRON SCATTERING LAW

Egelstaff, P.A.; Schofield, P.
Nucl. Sci. Engineering 12, p. 260-270, (1962).

The magnitude of the scattering cross section for slow neutrons by atomic systems (gases, liquids, and polycrystalline solids) is governed by the correlated motions of atoms in the system. A major contribution to the scattering is determined by the motion of single atoms. The dominant part of this contribution is determined by the velocity autocorrelation function for an atom in the system. The aim of this paper is (i) to show how the auto-correlation function can be derived from experimental scattering data for small momentum transfers and (ii) to give methods of evaluation of the corresponding part of the cross section for all momentum and energy transfers in terms of the experimentally observed quantities. The methods are chosen to minimise computational difficulties and inaccuracies. The comparison of the recomputed data with the experimental results permits the estimate of other contributions to the scattering. Some simple examples of these methods are given, and the relevance of this work to thermal neutron transport calculations is mentioned.

ELLIOTT

THEORY OF NEUTRON SCATTERING FROM LIQUID AND SOLID HYDROGEN

Elliott, R.J.; Hartmann, W.M.
Proc. Phys. Soc. 90, p. 671-680 (1967).

The inelastic spectrum of cold neutrons scattered incoherently from condensed hydrogen shows a quasi-elastic peak and an ortho-para conversion peak. A theory is developed to calculate the broadening of these peaks due to the hindering of the rotation of ortho-hydrogen molecules by anisotropic inter-molecular interactions. The quadrupole-quadrupole, van der Waals and valence interactions are taken between pairs of molecules and contributions to the broadening up to the first power of the ortho concentration are discussed. The quadrupole-quadrupole term is seen to be dominant, broadening the ortho-para peak in agreement with experiment but contributing a width to the quasi-elastic peak which is less than the resolution broadening. The theory is extended to the analogous incoherent scattering peaks in deuterium with similar results.

GALOTTO

COLD NEUTRON SMALL ANGLE SCATTERING DEVICE FOR TECHNOLOGICAL APPLICATIONS

Galotto, C.P.; Pizzi, P.; Walther, H. (FIAT, D.C.R., Laboratori Centrali, Torino, Italy); Angelastro, V.; Cerullo, N.; Cherubini, G. (Centro Applicazioni Militari Energia Nucleare, S. Piero a Grado (Italy))

Nucl. Instrum. Methods (Netherlands) 134:2. 369-378 (1976 April).

The neutron small-angle scattering device set up at the Camen Galileo Reactor in Pisa is described in detail. In particular the performance of the liquid propane cold source, guide tube, wavelength selector, detection and electronic data processing system are examined. The system allows low-angle measurements at scattering vectors between approximately 10^{-3} and $2 \times 10^{-1} \text{ \AA}^{-1}$. Some technological applications related to structural modifications occurring in turbine blades, dislocations evolution in fatigued poly crystalline nickel and ferritic phase formation in welded AISI 304, are briefly reported.

GANGWANI

THERMAL-NEUTRON TRANSPORT PROCESSES IN H_2O - D_2O MIXTURES IN THE TEMPERATURE RANGE 253 TO 21 K: THE POSSIBLE USE OF THESE MODERATORS AS COLD-NEUTRON SOURCES

Gangwani, G.S. (Dyal Singh College, New Delhi); Tewari, S.P.; Kothari, L.S.

Nucl. Sci. Eng. (United States) v 61:1. p. 78-79 (1976 Sept.).

The results of calculations of time-dependent, space-dependent, and steady-state neutron spectra in different assemblies of various H_2O - D_2O (ice) mixtures in the temperature range of 253 to 21 K are reported. By the matrix diagonalization method, the multigroup Boltzmann diffusion equation was solved to obtain asymptotic and transient spectra in assemblies at 253 K, with buckling values ranging from 0 to 0.4 cm^{-2} . Mixtures with D_2O content of 20, 50, and 80 wt percent are considered. For some selected assembly sizes, the optimum H_2O - D_2O mixtures that would give maximum cold-neutron flux were determined. The optimum mixtures for buckling values of 0.1113, 0.0158, and 0.001 cm^{-2} are those with nearly 30, 70, and 90 percent D_2O , respectively; the corresponding gain factors for graphite-filtered neutrons are 1.85, 4.17, and 13.57, respectively.

GRANADA

APPLICATION OF A SYNTHETIC MODEL TO THE DESCRIPTION OF NEUTRON SCATTERING PROPERTIES OF LIQUID H_2 AND D_2

Granada, J.R.; Gillette, V.H.; Mayer, R.E.

Physica B 156 & 157, 164-167 (1989)

The interaction of slow neutrons with liquid H_2 and D_2 is described in a simple way with the use of a synthetic scattering function. The analytical expressions derived from this model allow a very fast evaluation of the total cross section as well as the isotropic and the anisotropic energy-transfer kernels. From these, neutron scattering and transport properties are calculated and compared with available experimental results for both liquids.

HAGEN

DESIGN AND MANUFACTURE OF A COLD-NEUTRON SOURCE FOR THE DANISH RESEARCH REACTOR DR 3

Hagen, H.; Leth, J.A.

Danish Atomic Energy Commission, Roskilde

Conference title: Symposium on irradiation facilities for research reactors, Teheran, Iran

Publ: International Atomic Energy Agency, Vienna, STI/PUB/316 p. 271-279 (1973).

The paper describes the design, development and manufacturing of a cold-neutron source at present being assembled and tested. The cold-neutron source of DR 3 is based on supercritical hydrogen at about 25°K as the moderator. This makes it possible to adjust the hydrogen density in the moderator chamber by small changes in the gas temperature. The necessary cooling capacity is supplied by two Philips Stirling B20 cryogenerators. The hydrogen is circulated between these cryogenerators and the in-pile moderator chamber by small fans. The safety of the facility is based on the use of triple containment preventing contact between hydrogen and air. The triple containment is achieved by enclosing the high vacuum system, surrounding the hydrogen system, in a helium blanket.

HARIG

STUDY OF LIQUID HYDROGEN AND LIQUID DEUTERIUM COLD NEUTRON SOURCES

Harig, H.

Primary Report No.: CEA-R--3505

Note: Thesis. Submitted to Grenoble Univ., France.

Language: French

CONTAINER DESIGN FOR THE DEUTERIUM SYSTEM OF THE COLD NEUTRON SOURCE IN THE HIGH FLUX REACTOR AT GRENOBLE WHEN TAKING IN ACCOUNT THE EXPLOSION OF A STOCHIOMETRIC DEUTERIUM-AIR MIXTURE

Harig, H.D.; Reutler, H.

Kernforschungszentrum, Karlsruhe, F.R. Germany

Primary Report No.: KFK--1451, p. 21 (1971)

Language: German

The detonation of a stoichiometric deuterium-air mixture at atmospheric pressure has been supposed as the maximum accident in the container system. We calculate with two different methods the consequences of such an explosion for two containers belonging to this system, one of zircaloy and the other of stainless steel. At first we use an empirically established formula from explosion experiments with TNT. Secondly we calculate the movement of the container wall, based on given peaks and developments of detonation pressures. Furthermore we estimate the possible pressure peaks of the reflected shock waves and their effect on surrounding materials. The result shows that a container being designed for the simple detonation pressure must not burst, even if the pressure of the reflected shock waves is several times higher than the design pressure.

COLD NEUTRONS

Harig, H.D.

Kernforschungsanlage, Juelich, F.R. Germany

Umschau Wiss. Tech., v. 72, no. 1, p. 25-26 (1972)

Language: German

HAUTECLER

A SYSTEMATIC STUDY OF COLD-NEUTRON SOURCES. "INELASTIC SCATTERING OF NEUTRONS IN SOLIDS AND LIQUIDS"

Hautecler, S.; van Dingenen, W.

Centre d'Etude de l'Energie Nucleaire, Mol, Belg.

Publ: International Atomic Energy Agency, STI/PUB/35, p. 453-474 (1961)

Language: French

Measurements of the inelastic scattering of cold neutrons improve in direct relation to an increase in the intensity of the source. The number of cold neutrons emitted by a limited quantity of moderator, brought to a low temperature and situated in a thermal neutron stream depends on various parameters: temperature, dimensions and nature of the moderating material. To obtain a better understanding of the influence of these different factors on the moderating power, measurements of effective temperature were taken out-of-pile with a cryostat which allowed the moderator dimensions to be changed. The substances investigated were graphite, beryllium, water, and the organic compounds acetone, benzene, paraffin, petroleum ether, butane and methane. With the results of these measurements the most suitable values can be selected for the parameters governing a cold source. These preliminary measurements were followed by spectrum measurements on a cold-neutron source placed in the centre of the BR-1 reactor. Using a crystal spectrometer, we have so far measured that part of the spectrum lying beyond the beryllium cut-off (wave-lengths greater than 4A) for the moderators acetone, benzene, petroleum ether, methyl alcohol and methane. The variation of the spectrum with moderator temperature was determined between the operating temperature of the reactor and the temperature of liquid nitrogen.

HENDERSON

PRELIMINARY ANS (ADVANCED NEUTRON SOURCE) REACTOR COLD SOURCE GAIN FACTOR CALCULATIONS FOR LIQUID DEUTERIUM AND LIQUID NITROGEN-15

Henderson, D.L.

Report: ORNL/TM--10824, p. 34 (1988 Nov.).

Individual energy group gain factors are computed for liquid nitrogen-15 and liquid deuterium cold source moderators using simple one-dimensional slab and spherical geometry calculational models. The calculations indicate that the optimum thickness for neutron transmission through a slab given an isotropic incident flux is, for wavelengths above .6 nm, approximately .20 m for liquid deuterium and .30 m for liquid nitrogen-15. The gain factors at .8 nm corresponding to these thicknesses are 15 for liquid deuterium and 3 for measurements on a cold-neutron source placed in the centre of the BR-1 reactor. Using a crystal spectrometer, we have so far measured that part of the spectrum lying beyond the beryllium cut-off (wave-lengths greater than 4A) for the moderators acetone, benzene, petroleum ether, methyl alcohol and methane. The variation of the spectrum with moderator temperature was determined between the operating temperature of the reactor and the temperature of liquid nitrogen.

PRELIMINARY ANS (ADVANCED NEUTRON SOURCE) REACTOR COLD SOURCE
GAIN FACTOR CALCULATIONS FOR LIQUID DEUTERIUM AND LIQUID
NITROGEN-15

Henderson, D.L.

Report: ORNL/TM--10824, p. 34 (1988 Nov.)

Individual energy group gain factors are computed for liquid nitrogen-15 and liquid deuterium cold source moderators using simple one-dimensional slab and spherical geometry calculational models. The calculations indicate that the optimum thickness for neutron transmission through a slab given an isotropic incident flux is, for wavelengths above .6 nm, approximately .20 m for liquid deuterium and .30 m for liquid nitrogen-15. The gain factors at .8 nm corresponding to these thicknesses are 15 for liquid deuterium and 3 for liquid nitrogen-15. The spherical geometry analysis showed that the cold neutron current below 10 meV into the cavity of a .16 m thick liquid deuterium spherical shell exceeds the neutron leakage current from a .38 m diameter liquid deuterium sphere. 15 refs.; 24 figs.; 7 tabs.

PRELIMINARY ONE-DIMENSIONAL NEUTRONICS SCOPING STUDY FOR A
CALIFORNIUM-252 COLD-NEUTRON SOURCE MODERATING DEVICE

Henderson, D.L.; Alsmiller, R.G. Jr.

Oak Ridge National Lab., TN USA

Nucl. Instrum. Methods Phys. A: A280:1. p. 91-94, (1989 August).

One-dimensional neutron transport calculations have been performed for a proposed californium cold-neutron source experimental facility. The computations indicate that a peak cold-neutron flux (flux below 10 meV) of 1.4×10^{13} neutrons/m²s can be attained from a 500 mg californium neutron source. The cold-neutron exit (leakage) current from the spherical cryostat containing the liquid deuterium is 2.2×10^{12} neutrons/m² s.

HOFFMAN

NATURAL CONVECTION COOLING OF A COLD NEUTRON SOURCE WITH
VAPORIZING DEUTERIUM AT TEMPERATURES OF 25 K

Hoffman, H.; Kakac, S.; Aung, W.; Viskanta, R.

Kernforschungszentrum Karlsruhe, Institut für Reaktorbauelemente, D 7500 Karlsruhe
'Natural Convection: Fundamentals and Applications', p. 1140-1154, Hemisphere
Publishing, New York, NY (1985).

In the High Flux Reactor (HFR) at Grenoble a new horizontally arranged cold neutron source will be installed that uses liquid deuterium (D₂) as the moderator for cold neutrons. This cold source should provide a high neutron flux, it should be simple in design, and be characterized by high reliability and by safe operation. A high neutron flux calls for installation of the cold source near the HFR core and good moderation requires a D₂ volume of 5 litres. Hence, the moderator, contained in a horizontally arranged cylindrical cell of 21 cm diameter and 20 cm length, is installed at the end nearest to the core of a horizontal beam tube of roughly 4.5 m length with an inner diameter of only 23 cm (Fig. 1). The HFR will be equipped with a second cold neutron source. The installation in the existing horizontal beam tube together with the amount of heat released determined the problems to be solved: the liquid content of the moderator cell must be high; the coolability of the upper cell walls must be guaranteed; the natural convection loop must be safe in operation.

INOUE

COLD NEUTRON PRODUCTION AND APPLICATION

Inoue, K. (Hokkaido Univ., Sapporo (Japan)); Watanabe, N.
Nippon Genshiryoku Gakkaishi (Japan) v 18:3. p. 129-136 (1976 March)
Language: Japanese. English translation AECL-tr-MISC-922 (1985).

The first part gives general introduction to cold neutrons, namely the definition and the role as a probe in basic science and technology. The second part reviews various methods of cold neutron production. Some physical characteristics required for cold moderators are presented, and a list summarizes a number of cold moderators and their reactor physics constants. The definition of flux gain factor and the measured values for liquid light- and heavy-hydrogen are also given. The cold neutron spectra in methane and liquid hydrogen measured by LINAC time-of-flight method are presented to show the advantage of solid methane. The cold neutron sources using experimental reactors or linear accelerators are explained along with the examples of existing facilities. Two Japanese programs, the one is the use of a high flux reactor and the other is the use of a LINAC, are also presented. The third part of this report reviews the application areas of cold neutrons.

20 K METHANE MODERATOR AND ITS APPLICABILITY TO AN INTENSE PULSED COLD NEUTRON SOURCE

Inoue, K.
Hokkaido Univ., Sapporo (Japan) Dept. of Nuclear Engineering
Nucl. Instrum. Methods Phys. Res. (Netherlands) 216:3. p. 537-538 (1983 Nov.)
Note: Letter-to-the-editor

A summary of performances of various cold moderators for a pulsed cold neutron source and a brief discussion of 20 K methane as appropriate moderator for intense pulsed source are given.

INSPEC

COLD NEUTRONS: SOURCES AND APPLICATIONS. JANUARY 1975-FEBRUARY 1988

(Citations from the INSPEC: Information Services for the Physics and Engineering Communities data base).

National Technical Information Service, Springfield, VA (USA)
Report No.: PB-88-859004/XAB 87 p. (1988 March).

This bibliography contains citations concerning cold neutron sources from a research reactor, the use of liquid hydrogen or deuterium to enhance the thermal equilibrium, the storage and lifetime of cold neutrons, neutron guides and transport to direct the beam to a test specimen, and a few specific applications as nondestructive test instrumentation. Test instrumentation includes neutron radiography, microscopy, spectrometry, and diffractometry. Tests are related to crystal lattice studies in inorganic compounds, determination of inhomogeneities in thin films, and fundamental physics experiments. (Contains 188 citations fully indexed and including a title list).

JACROT

NEUTRON COOLING AND COLD-NEUTRON SOURCES

Jacrot, B.

Centre d'Etudes Nucleaires, Saclay, France

"Pile Neutron Research in Physics"

Publ: International Atomic Energy Agency, STI/PUB/36, p. 393-408 (1962)

Language: French

Intense cold neutron sources are useful in studying solids by the inelastic scattering of neutrons. A general survey is presented of the following aspects; theoretical considerations regarding thermalization processes at very low temperatures; experiments comparing moderators; and the operating cold neutron sources and their results.

JENSEN

COLD NEUTRON SOURCE IN DR 3

Jensen, K.; Leth, J.A.

Risoe National Lab., Roskilde (Denmark)

Report No.: RISO-M-2246, 40 p. (1980 Sept.)

A description of the cold neutron source in DR 3 is given. The moderator of the cold neutron source is supercritical hydrogen at about 30 K and 15 bar abs. The necessary cooling capacity is supplied by two Philips Stirling B20 cryogenerators. The hydrogen is circulated between the cryogenerators and the in-pile moderator chamber by small fans. The safety of the facility is based on the use of triple containment preventing contact between hydrogen and air. The triple containment is achieved by enclosing the high vacuum system, surrounding the hydrogen system, in a helium blanket. The achieved spectrum of the thermal neutron flux and the gain factor are given, as well as the experience from more than 5 years of operation. Finally, some work on extension of the facility to operate two cold sources is reported.

COLD NEUTRON SOURCES: EXTENDING THE USEFULNESS OF RESEARCH REACTORS

Jensen, K.; Stein, J.

Risoe National Lab., Roskilde, Denmark; Internationale Atomreaktorbau G.m.b.H., INTERATOM, Bergisch Gladbach, Germany, F.R.

Nucl. Eur. (Switzerland) v 5:6, p. 16-19, 1985 Jun.

An introduction to cold neutrons and their uses is given. Existing and planned cold neutron sources (CNS) are listed. The principles of hydrogen-gas CNSs are explained, including their safety philosophy. Super-critical hydrogen systems are discussed. Experience with Risoe's CNS is communicated.

JINGHUI

MEASUREMENT OF THE FILTRATED COLD NEUTRON SPECTRUM AT THE BEAM HOLE OF HEAVY WATER REACTOR (IAE)

Jinghui, R.; Cheng, G.; Guiying, C.; Huiming, Z.; Tonghua, Y.; Zhixu, C.
Institute of Atomic Energy, Academic Sinica
Hekexue Yu Gongcheng (China) v 4:4, p. 188-190, 1984 June
Language: Chinese
Work Location: China

KALLI

MONTE CARLO CALCULATIONS OF A HYDROGEN COLD NEUTRON SOURCE Kalli, H.

Helsinki Univ. of Tech., Otaniemi, Finland
Acta Polytech. Scand., Phys. Nucl. Ser., no. 88, p. 1-28, (1972).

This paper discusses the results of Monte Carlo calculations of a hydrogen cold-neutron source in a tangential beam tube configuration. In the calculations the shape of the cold-neutron source was cylindrical with half-spherical ends and its diameter fixed. Its length was optimized. The calculations were performed for hydrogen at two different temperatures: (1) for gaseous hydrogen at 35 K by varying the source length, the pressure and the relative ortho/para abundance, (2) for liquid hydrogen at 20.4 K by varying the source length and the relative ortho/para abundance. In both cases the optimal length was about 40 cm and hence the cold-neutron source obtained differed radically from the previous cold-neutron sources. Contradictory to some earlier results, parahydrogen was found to be a better cold-neutron source material than orthohydrogen.

HYDROGEN COLD NEUTRON SOURCE CALCULATIONS FOR DIFFERENT ORTHO/PARA MIXTURES

Kalli, H.
Helsinki Univ. of Tech.
Nucl. Instrum. Methods, 113:3, p. 461-463 (1973).

The results of Monte Carlo calculations of a cylindrical hydrogen cold neutron source in a tangential beam tube are discussed. The dependence of the cold neutron output on the relative ortho/para abundance was studied at the hydrogen boiling temperature 20.4 K. With a suitable choice of moderator cylinder length the output was found to be independent of the ortho/para mixture. The maximum output was obtained with a mixture rich in parahydrogen.

MONTE CARLO COMPARISON OF HYDROGEN COLD-NEUTRON SOURCES IN RADIAL AND TANGENTIAL BEAM-TUBE ARRANGEMENTS

Kalli, H.
Nucl. Instrum. Methods. 118:1, p. 61-71 (1974 June 01).

A Monte Carlo comparison of the moderating efficiency of various hydrogen cold-neutron sources in the radial and in the tangential beam-tube arrangements is described. In the calculations, the length and the relative ortho-para abundance of cooled gaseous- and liquid-hydrogen moderator cylinders were varied. Maximum cold-neutron outputs were obtained by long moderator cylinders rich in parahydrogen in the tangential arrangement. It was found that with a suitable (non-optimal) choice of the moderator length the total cold-neutron output could be almost independent of the ortho-para mixture.

MONTE CARLO STUDIES OF NEUTRON TRANSPORT IN COLD NEUTRON FACILITIES

Kalli, H.

Helsinki Univ. of Technology, Otaniemi (Finland). Dept. of Technical Physics

Report No.: INIS-mf-1897

Thesis (D.Tech.) consists of five previously published papers.

KAWABATA

NEUTRON IRRADIATION EFFECTS AT CRYOGENIC TEMPERATURE ON THE STRUCTURAL MATERIALS FOR COLD NEUTRON SOURCE

Kawabata, Y.; Takahashi, H.

Japan Atomic Energy Research Inst., Tokyo

Report No.: JAERI-M-86-139

Language: Japanese.

In recent years, the demand for cold neutrons is growing in neutron scattering research. According to such requirements the cold-neutron source (CNS) is planned for the upgraded JRR-3. The moderator cell in CNS, which contains liquid hydrogen, will be irradiated for long time by high fluence in the deuterium reflector region. The moderator cell has to endure quite a wide range of temperatures from the liquid hydrogen temperature (about 20 K) to high temperature (about 400 deg C). Therefore the moderator cell, with quite thin thickness and ovoid shape, to moderate and draw out neutrons effectively, must have a high mechanical strength to contain liquid hydrogen under severe conditions. In this report, the mechanical tests on the materials for the moderator cell after irradiation at cryogenic temperatures are reviewed, and the mechanical strength of the materials for the moderator cell are discussed. It is shown that A286 is the best material for the moderator cell, and it will keep enough strength during the operational period of the cold neutron source installed in the upgraded JRR-3.

KAWAI

COLD NEUTRON FACILITY ON KUR, 1. ITS CONSTRUCTION AND TEST OPERATIONS OUTSIDE THE REACTOR

Kawai, T.; Sugimoto, M.; Okamoto, S. (Kyoto Univ., Kumatori, Osaka (Japan). Research Reactor Inst.)

Annu. Rep. Res. React. Inst., Kyoto Univ. (Japan) v 13. p. 105-11 (1980 Nov. 13).

The purpose of this report is to describe the system structure and thermal problems related to the design of a proposed cold neutron facility for a high flux reactor. The cryogenic system consisted of a helium refrigerator (60 W at 20 K), a condenser and a liquid hydrogen moderator cell of 1 L was constructed as a cold neutron facility in the KUR graphite thermal column. This system was tested outside of the reactor building for investigating the operation characteristics at start-up, normal, transient and shut-down operations under a constant or periodic thermal load. The liquefaction capacity in the condenser was 25.3 W at 21 K, which is about 50% of the design capacity. As a result, the facility has to be located in such a position where nuclear heat is smaller than 23 W at 21 K. In order to check the response of the cryogenic system to the change of thermal load, a change of pressure in the reservoir tank was investigated by varying heat load which is supplied from electric heating coils around the periphery of the moderator cell. From the Bode's diagram obtained by

experiments, it was shown that such a cryogenic system has a characteristic of self regulation to the thermal disturbance in the region of 30% of the maximum heat absorption capacity.

SELF-REGULATING CHARACTERISTICS OF A COLD-NEUTRON SOURCE WITH A CLOSED-THERMOSIPHON

Kawai, T.; Utsuro, M.; Maeda, Y.; Ebisawa, T.; Akiyoshi, T.; Yamaoka, H.; Okamoto, S. Kyoto University, Research Reactor Inst.

Nucl. Instrum. Methods Phys. Res. (Netherlands) A276:3 p. 408-412, 1989 April 1.

This report describes self-regulating properties of the Kyoto University Reactor (KUR) Cold-Neutron Source (CNS), which is cooled by a closed-thermosiphon loop of hydrogen, as are most of the CNS constructed recently. The circular moderator transfer tube is in a plane inclined about 14 degrees to the horizontal plane. The hydrogen-helium cryogenic system of the CNS shows a self-regulating characteristic under thermal disturbances, if they are smaller than about 30% of the practical allowable heat load, 300 W at 25 K in our case. This self-regulating characteristic has been confirmed from Bode's diagram of the hydrogen pressure response in the reservoir tank to the heat load modulation. Due to this property, the liquid level in the moderator cell is kept almost constant during long term operation of the reactor. Measurements of the vertical distribution of the cold-neutron flux from the moderator cell showed that a sufficient amount of liquid was stored in the cell and the ratio of the fraction of cold neutrons in the cold moderator to that in the ambient moderator was measured to be about 20 where the wavelengths are longer than 6 Å using liquid hydrogen as a moderator.

KEINERT

INVESTIGATION OF NEUTRON SCATTERING DYNAMICS IN LIQUID HYDROGEN AND DEUTERIUM FOR COLD NEUTRON SOURCES.

Keinert, J.; Sax, J.

Stuttgart Univ., F.R. Germany, Inst. fuer Kernenergetik und Energiesysteme Kerntechnik v 51:1. p. 19-23 (1987 Aug.)

Starting from the basic theory of Koppel and Young for neutron scattering dynamics in hydrogen and deuterium, an improved model is derived for the liquid phase of these moderators. The free translations of the molecule are replaced by the superposition of a solid-state-like motion and a hindered translation. As a data base, scattering-law data in ENDF/B-5 format were generated for the ortho- and para-modifications at different temperatures. For validation, a lot of differential and integral neutron scattering cross-section experiments were recomputed both for the liquid phase model and the Koppel-Young theory.

KEVEY

DESIGN AND SAFETY ANALYSIS OF THE COLD NEUTRON SOURCE AT THE BROOKHAVEN HIGH-FLUX BEAM REACTOR

Kevey, A.

BNL Report 21017 (1976)

KOEPPPE

TEMPERATURE MEASUREMENTS IN THE COLD NEUTRON SOURCE AT THE REACTOR FRJ-2.

Koepppe, W.; Leyers, H.J.
Kernforschungsanlage, Juelich, F.R. Germany
Kerntechnik 13: No. 12, 553-6 (1971 Dec.).

During the first phase of commissioning (cold trials) the entire facility was tested out-of-pile under simulated reactor conditions. A particularly important part of these trials related to testing the functional reliability of the thermosiphon system; this entailed measuring temperatures and temperature differences in the range from about 14 to 20 K, with a relatively high accuracy. It was also necessary to test the cooling-down performance of the entire facility; this entailed measuring temperatures in the range from about 14 to 300 K but with less stringent accuracy tolerances. The second and the third commissioning phase trials were conducted in-pile, which considerably restricted the possibility of measuring temperatures in the ranges stated above. This relates especially to the thermal tempering of the temperature sensors used and to the not exactly known, but certainly present, effects of the reactor irradiation on the temperature characteristic of the sensors.

KONOPLEV

RESEARCH HIGH FLUX REACTOR PIK

Konoplev, K.A.
Leningrad Institute of Nuclear Physics, Gatchina USSR
IAEA TECDOC 410, p. 409-421 (1987 March).

The reactor now under construction will have a thermal flux of $10^{15} \text{ cm}^{-2}\text{s}^{-1}$. A liquid deuterium cold source and neutron guide hall are planned.

KOPPEL

SLOW NEUTRON SPECTRA IN MOLECULAR HYDROGEN AT LOW TEMPERATURE

Koppel, J.U.; Young, J.A.
Nukleonik 8, p. 40-45 (1965)

The integral properties of the scattering cross-section for molecular hydrogen at low temperature have been computed. In addition, neutron spectra for both space-independent and space-dependent geometries have been calculated at 20.4°K, the boiling temperature of liquid hydrogen.

KOTTWITZ

THERMAL NEUTRON FLUX SPECTRUM IN A MEDIUM WITH A TEMPERATURE DISCONTINUITY

Kottwitz, D.A.
Hanford Laboratories, Richland, Washington
Nucl. Sci. Eng 7, 345-354 (1960).

The energy-dependent diffusion equation in the heavy gas approximation is considered for the case of a single medium which has absolute temperature T_1 in one halfspace and T_2 in the other. The steady-state solution for $F(x,E)$, the neutron flux per unit energy, is obtained in the absence of sinks and sources. Although the formal series solution diverges under certain conditions, it can be "summed" by means of the Euler transformation. Two approximation schemes giving simple analytical results are discussed. Numerical results for flux spectra and the total neutron density are presented for the case in which the temperature ratio is 2:1. The connection between this work and the theory of irreversible processes is briefly indicated.

KRAEHLING

SAFETY REPORT FOR THE TEST RIG OF THE COLD NEUTRON SOURCE AT FRM
Sicherheitsbericht fuer den Testaufbau der Kalten Neutronenquelle am FRM
Kraehling, E.
Technische Univ. Muenchen, Garching F.R. Germany
Fakultaet fuer Physik, INIS-mf-11682, 66 p. (1986 July).
Language: German

In order to raise the flux of long wave neutrons at the Munich Research Reactor (FRM), a so-called cold neutron source is to be installed, in which liquid hydrogen is used as the refrigerated moderator. As a preliminary stage, a test rig is installed outside the reactor pool in the reactor hall, with which, together with complete parts of the plant, a trial run with liquid hydrogen is to be carried out. Before the planned trial run with liquid hydrogen, several test runs were done with refrigerated helium gas in the hydrogen system. The planned design data were confirmed from the operating data obtained, so that the intended control behaviour of the refrigeration plant and the functioning of the important operating and safety devices could be proved.

KRUEGER

BRIDGE - A COMBINED DIFFUSION/TRANSPORT PROGRAM TO CALCULATE
A COLD NEUTRON SOURCE AT THE FRG-I
Krueger, A.; Turgut, M.H.
GKSS-Forschungszentrum Geesthacht G.m.b.H., Geesthacht-Tesperhude (Germany, F.R.). Inst. fuer Physik
Annual meeting on nuclear technology '85. Proceedings. Session 1: Reactor physics
Munich, F.R. Germany, 1985 May 21
Publ: Deutsches Atomforum e.V., Bonn, F.R. Germany, CONF-850557-Summ., p. 63-66 (1985).
NOTE: Published in summary form only; see also Turgut 85
Language: German

INCREASE OF THE SUBTHERMAL NEUTRON FLUX BY USING A COLD
NEUTRON SOURCE AT THE FRG-1. FINAL REPORT
Krueger, A.; Turgut, M.H.
GKSS-Forschungszentrum Geesthacht G.m.b.H., Geesthacht-Tesperhude (Germany, F.R.). Inst. fuer Physik
GKSS-86/E/9, p. 38 (1986).

The increase of the subthermal neutron flux (wavelength range 4-6 Å) by a cold neutron source (CNS) at a radial beam tube of the FRG-1 reactor is investigated in combination with

different reflectors (H_2O , C, Be, D_2O). Advantage factors on the basis of the directed neutron flux, resulting from the use of the CNS, are calculated for various configurations. In addition, the influence of different scattering models (gas, Koppel/Young) for the CNS, group structure, and structural materials are described. Finally, the CNS assembly which is going to be installed at the FRG-1 is treated in detail. For the calculations the transport code NEUTRA and the spectral code GGC-4 are used. 23 figs.; 6 tabs.

KRULL

COLD NEUTRON SOURCE WITH THE FRG-1 RESEARCH REACTOR

Krull, W.

GKSS-Forschungszentrum Geesthacht G.m.b.H., Geesthacht-Tesperhude (Germany, F.R.)

Zentralabteilung Forschungsreaktoren, ATW, Atomwirtsch., Atomtech. (Germany, Federal Republic of) v 33:1, p. 43-47 (1988 Jan).

Language: German

The approximately thirty-year-old FRG-1 research reactor of the GKSS Geesthacht Research Center will be equipped with a cold neutron source to increase the neutron flux for improved utilization of the beamhole experiments. The facility, which was installed by the Interatom/Riso Research Center consortium, is currently in the commissioning phase of its subsystems and will start continuous operation with the FRG-1 at full power in early 1988. The experimental facilities of the cold neutron source are to be employed chiefly for materials research. Future areas of study will include the influence of impurities on the strength of steel, high-temperature materials, metallic glasses, hydrogen zones in materials welded under water, and changes in materials properties under conditions of use. The cold neutron source has been designed so that no credible accident or combination of accidents and incidents or failure of the active safety measures can jeopardize the FRG-1 plant or third parties.

KUMAI

FUNDAMENTAL EXPERIMENTS ON CLOSED THERMOSYPHON FOR JRR-3 COLD NEUTRON SOURCE, (1)

Kumai, Toshio; Sakamoto, Masanobu; Takahashi, Hidetake; Shinozu, Kazuo

Japan Atomic Energy Research Inst., Tokyo

Report No.: JAERI-M-87-006, p. 22 (1987 Feb.)

Language: Japanese

An experimental study has been performed to understand the characteristics of the closed two-phase thermosyphon, using Freon-113 as the working fluid, for the JRR-3 cold neutron source which has a double wall thermosyphon system. The experimental apparatus was made of glass in order to permit visual and photographic observations. The purposes of this experiment were mainly focused on the effect of the presence of inner tube on the heat transfer limit, the visual observations of the flow conditions of fluid and the condensation conditions of fluid in the condenser. It is found that in the case of the single tube, experimental results on the heat transfer limit agree with the values which are given by Wallis's correlation equation, whereas in the case of the double tube, the presence of the inner tube increases the heat transfer limit by about 200 W.

LETH

DESCRIPTION OF A COLD NEUTRON SOURCE IN DR 3

Leth, J.A.

Danish Atomic Energy Commission, Risoe. Research Establishment
RISO-M-1676, p.1-38 (1974).

A description of the cold-neutron source in DR 3 is given. The moderator of the cold-neutron source is supercritical hydrogen at about 25 K and 15 bar abs. The necessary cooling capacity is supplied by two Philips Stirling B20 cryogenerators. The hydrogen is circulated between the cryogenerators and the in-pile moderator chamber by small fans. The safety of the facility is based on the use of triple containment preventing contact between hydrogen and air. The triple containment is achieved by enclosing the high vacuum system, surrounding the hydrogen system, in a helium blanket.

NOTE: see also Jensen

LILLIE

DESIGN CALCULATIONS FOR THE ANS (ADVANCED NEUTRON SOURCE) COLD SOURCE

Lillie, R.A.; Alsmiller, R.G. Jr.

Oak Ridge National Lab.

Conf-8810182--3, p. 23, 'International Collaboration on Advanced Neutron Sources', ICANS X, Los Alamos (1988 October).

The calculation procedure, based on discrete ordinates transport methods, that is being used to carry out design calculations for the advanced neutron 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. Calculated results are also presented that indicate how the flux of cold neutrons varies with cold source parameters. 23 refs.; 5 figs.; 3 tabs.

LOVSETH

THE SCATTERING OF SLOW NEUTRONS BY DIATOMIC MOLECULES

Lovseth, J.

Physica Norvegica 1, 127-139 (1962).

The derivation of the formulae for neutron scattering by homonuclear diatomic molecules using the Fermi pseudopotential in conjunction with the Born approximation is outlined. The quantum mechanical state of the system before and after the interaction is taken into account in a detailed manner. Numerical results are presented for H₂, D₂, N₂ and O₂ and compared with available experimental data. The properties of H₂ and D₂ as cold moderators are discussed briefly.

MACFARLANE

COLD MODERATOR SCATTERING KERNELS

MacFarlane, R.E.

Los Alamos National Laboratory

Proc. ICANS X, p. 157-176 (1988 October 3-7)

Report LA-UR-88-3358.

New thermal scattering law files in ENDF format have been developed for solid methane, liquid methane, liquid ortho and para hydrogen, and liquid ortho and para deuterium using up-to-date models that include such effects as incoherent elastic scattering in the solid, diffusion and hindered vibration and rotations in the liquids, and spin correlations for the hydrogen and deuterium. These files were generated with the new LEAPR module of the NJOY Nuclear Data Processing System, and other modules of this system were used to produce cross sections for these moderators in the correct format for the continuous-energy Monte Carlo code MCNP being used for cold-moderator-design calculations at the Los Alamos Neutron Scattering Center LANSCE.

MERRETT

DESIGN OF A LIQUID HYDROGEN COLD NEUTRON SOURCE FOR THE 6H HOLE IN DIDO

Merrett, D.J.; Pearce, D.G.; Webb, F.J.

Atomic Energy Research Establishment, Harwell (England)

Report No.: AERE-M--1690, p. 62 (1966)

MICHAUDON

NEW INTENSE SOURCE OF VERY-COLD AND ULTRA-COLD NEUTRONS

Michaudon, A.

Institut Max von Laue - Paul Langevin, 38 - Grenoble, France

International Atomic Energy Agency neutron source meeting Leningrad, USSR 1986 Jun 9

IAEA-TECDOC-410; CONF-8606126 p. 421-427 (1987 Mar.).

This paper presents a new source of very cold and ultra-cold neutrons recently put into operation at the High-Flux Reactor of the Institut Laue-Langevin in Grenoble (France). This source consists of a primary source of liquid deuterium, a set of metallic nickel vertical and curved guides and a neutron turbine. Results about the flux and density of very low energy neutrons are given both at the exit of the curved guide and after the neutron turbine. A preliminary list of experiments that will be carried out with this new source is also presented. 19 refs.; 5 figs.

MOON

THERMAL NEUTRON TRANSPORT NEAR A MODERATOR DISCONTINUITY USING THE METHOD OF WEIGHTED RESIDUALS. 2. COLD NEUTRON SOURCES

Moon, J.R.; Beynon, T.D.

Univ. of Birmingham, Eng.

J. Phys., D (London) 6: No. 4, 427-448 (1973 Feb. 28).

Using the method of weighted residuals, a detailed numerical study is made of the neutronics of spherical cold-neutron sources composed of liquid hydrogen and liquid deuterium in reactor moderators of light water, heavy water and graphite. Particular attention is paid to the physical effects at the cold-source boundary. The computations allow a number of conclusions to be made on the best designs of spherical cold-source configurations. It is found that for small spherical sources there is little difference in neutron gain using either normal-hydrogen or para-hydrogen, and that the largest gains are obtainable from large deuterium-filled sources.

NEEF

EVALUATION OF HYDROGEN DATA FOR COLD NEUTRON SOURCES AND THEIR APPLICATION TO SOURCE DESIGN STUDIES

Neef, R.D.; Schaal, H.

Kernforschungsanlage Juelich G.m.b.H., Germany, F.R. Inst. fuer Reaktorentwicklung
International conference on nuclear data for basic and applied science, Santa Fe, NM, USA,
1985 May 13.

Radiat. Eff. (United Kingdom) 96:1-4. p. 37-40 1986 March.

Evaluation of group cross sections of hydrogen at 20 K temperature and the Monte Carlo design calculations for the new cold source in the DIDO reactor in Juelich are discussed.

NIELSON

MEASUREMENTS OF THE FLUX FROM THE COLD SOURCE AT DR3

Als Nielsen, J.; Kjems, J.K.

RISO M 1802 (1975 May)

OLIVI

SURVEY MEASUREMENTS ON THE OPTIMALISATION OF THE SCATTERER SHAPE FOR A COLD NEUTRON SOURCE

Olivi, L.f Misenta, R.

European Atomic Energy Community, Ispra (Italy). Joint Nuclear Research Center
Report No.: EUR-2953.e, 12 p. (1966).

ONISHI

RECONSTRUCTION PROGRAM FOR JAPAN RESEARCH REACTOR NO. 3

Onishi, N.; Futamura, Y.; Sakurai, H.

Tokai Research Establishment, Japan Atomic Energy Research Institute,
Multipurpose Research Reactors, IAEA Symposium
IAEA STI/PUB/762, 79-90 (1988).

Japan Research Reactor No. 3 (JRR-3), had been operating since 1962. After 21 years of operation, an upgrading program was planned to respond to the demand for better neutron beam and irradiation conditions. The New JRR-3 is to be upgraded to a 20 MW(th), light water moderated and cooled, beryllium and heavy water reflected, pool type reactor using 20% low enriched UAl_x-Al (LEU) plate type fuel. Besides, nine horizontal beam tubes, one cold neutron source (vertical thermo-siphon circulation type), five neutron guide tubes (for

thermal and cold neutrons) and irradiation facilities will be installed. The new reactor is designed to produce maximum thermal and fast neutron fluxes each of more than 2×10^{14} n/cm²s.

PEARCE

LIQUID-HYDROGEN EXPLOSIONS IN CONTAINMENT VESSELS

Pearce, D.G.; Ward, D.L.; Hayes, P.

AERE-R 4584 (1966 Feb.).

The hazard evaluation of liquid-hydrogen moderator chambers in nuclear reactors demands a containment vessel that will prevent reactor damage should a fault occur permitting an explosion of liquid hydrogen and condensed solid air. Explosion trials in 1957 gave sufficient data for designing containment vessels for the BEPO reactor and a small hydrogen chamber in the DIDO reactor, but when large hydrogen chambers were proposed for the LIDO and DIDO reactors a much more comprehensive series of trials was carried out using purpose designed and constructed apparatus. A series of explosions of liquid hydrogen and solid air were performed in closed vessels. The proportions of hydrogen and air, the quantities in relation to the containment volume, and the containment volumes and L/D ratio themselves, were all varied, and the resulting pressures, variations, and peak pressures were measured against time. The full results are analysed here and compared with theoretical analyses. The dynamic response of typical containment vessels suitable for use in nuclear reactors is considered and compared with the time characteristics of the explosion forces. It was clear that relevant theories were difficult to locate despite intensive enquiries. Considerable scatter was observed in the results and apparent anomalies observed when evaluation explosion efficiencies. Nevertheless, despite these circumstances the series of experiments was useful and has contributed appreciably to a better understanding of the problems involved.

COLD NEUTRONS

Pearce, D.G.

Atomic Energy Research Establishment, Harwell, Eng.
Sci. J., 3: 55-60 (1967 Aug.).

The spectrum of neutrons emitted by an operating reactor covers a huge range of energies. Special techniques can filter out the higher energies to produce 'cold' neutrons of increased intensity for physics experiments which cannot be done without them.

A DESIGN STUDY OF THE COLD SOURCE FOR THE HARWELL HIGH-FLUX BEAM REACTOR.

AERE Harwell

Report No. AERE-R 5752, p. 1-54, (1968 April).

This report is divided into two sections. The first section starts with the early design proposed for the Harwell H.F.B.R. and shows, by a process of evolution, how two systems emerged as the most practical solutions to the problem, one a liquid-hydrogen source and the other a supercritical-gas system. The second section is devoted to a detailed analysis of the super-critical system, which is shown to be not only the more attractive technically, but also the cheaper.

PERSSON

AN EXPERIMENTAL STUDY OF COLD MODERATORS IN THE REACTOR R1

Persson P.

Royal Inst. of Tech. Stockholm, Sweden

J. Nucl. Energy 21, 701-712 (1967).

An experimental study of 18 cold moderator combinations has been performed in a 34-cm diameter channel in the thermal column of the heavy water reactor R1. Moderators investigated are: methyl alcohol, pentane, pentanol, light water and heavy water. All the moderators were cylinders of diameter 32 cm and the following thicknesses were used: 0.5, 1, 2, 3.5, 8, 12 and 20 cm. The moderators were cooled to 85°K by liquid nitrogen. A time-of-flight spectrometer was used for the analysis of the neutron spectra. The purpose of the experiments was to investigate the most efficient cold moderator for permanent installation in the reactor. The experimental data show that the greatest gain factor obtained at the neutron wavelength 4 Å is 2.9. This gain factor was obtained by use of a methyl alcohol or a pentane moderator at a thickness of 1 cm. The results are in disagreement with results predicted and obtained in experiments by some other authors.

PREUSSNER

INSTRUMENTATION OF THE COLD NEUTRON SOURCE AT THE REACTOR FRJ-2

Preussner, A.

Kernforschungsanlage, Juelich, F.R. Germany

Kernteknik 13: No. 12, 550-2 (1971 Dec.).

The problem consists in essence of measuring various operating parameters in order to make it possible to control manually the startup of the facility and to monitor the facility in operation. The decisively important parameters are the temperatures of the vacuum jacket tube and of the moderator pot. These temperatures are measured with NiCr-Ni thermocouples and are monitored in respect of critical limits by means of a compensation box, amplifiers and a moving coil galvanometer with inductive limit value relays.

RIEF

EFFECTIVITY OF HYDROGENOUS MODERATORS IN PULSED NEUTRON SOURCES

Rief, H.; Hartman, J.

Joint Nuclear Research Centre, Ispra, Italy

Annals of Nucl. Eng. 2, 521-539 (1975).

Monte Carlo calculations and heat deposition calculations for the SORA (pulsed nuclear reactor) project are described, and compared with the ZING spallation target at ANL. 9 tabs.; 7 figs.; 47 refs.

RITENOUR

THE SINGLE-COLLISION THERMALIZATION APPROXIMATION FOR APPLICATION TO COLD NEUTRON MODERATION PROBLEMS

Ritenour, R.L.; Rydin, R.A.; Mulder, R.U.

Transactions of the American Nuclear Society (USA) 59, 148 (1989).

The single collision thermalization (SCT) approximation models the thermalization process by assuming that neutrons attain a thermalized distribution with only a single collision within the moderating material, independent of the neutron's incident energy. The physical intuition on which this approximation is based is that the salient properties of neutron thermalization are accounted for in the first collision, and the effects of subsequent collisions tend to average out statistically. The independence of the neutron incident and outscattering energy leads to variable separability in the scattering kernel and, thus, significant simplification of the neutron thermalization problem. The approximation also addresses detailed balance and neutron conservation concerns. All of the tests performed on the SCT approximation yielded excellent results. The significance of the SCT approximation is that it greatly simplified thermalization calculations for CNS design. Preliminary investigations with cases involving strong absorbers also indicates that this approximation may have broader applicability, as in the upgrading of the thermalization codes.

ROGOV

STUDY ON THE PARAMETERS OF COLD NEUTRON MODERATORS USING THE MONTE CARLO METHOD

Rogov, A.D.

Joint Inst. for Nuclear Research, Dubna (USSR). Lab. of Neutron Physics

JINR-R-11-85-554, 7 p. (1985)

English translation AECL-tr-misc-00798.

The results of Monte Carlo analysis of neutron cold moderators are discussed. Module MCU is the base of a program for calculating the moderators. The program calculations include: the heat generation in a moderator due to neutron elastic scattering, vector neutron fluxes and neutron current from the moderator surface, neutron lifetime in moderator, effective temperature of neutron gas. The results of neutron-physical optimization of the cold neutron source (CNS) are given. The program for calculation of CNS is described. The calculations have been performed for heat generation in water and in liquid hydrogen. 14 refs.; 2 figs.; 1 tab.

ROWE

NBS COLD NEUTRON RESEARCH FACILITY

Rowe, J.M.; Greene, G.L. (ed.)

National Bureau of Standards, Gaithersburg, MD

Workshop on the investigation of fundamental interactions with cold neutrons,

Gaithersburg, MD, USA 1985 Nov. 14.

NBS/SP-711; CONF-8511137, p. 11-15, (1986 Feb.).

A large-volume heavy-ice cold moderator to be operated at 25K is being tested for insertion into a reserved space in the reactor early in 1986. This moderator will provide a large increase in available cold neutron ($\lambda > 4 \text{ \AA}$) flux, and can provide access for large number of neutron guide tubes. NBS has proposed the construction of a large (240' x 130')

experimental hall and associated instrumentation, which would be operated as a national facility. The NBS proposal includes funding for 11 experimental facilities, and reserves space for an additional 5 facilities to be developed by Participating Research Teams (PRT's). For the NBS developed stations, 2/3 of the available time would be reserved for use by the general US scientific community (to be scheduled by a Program Advisory Committee), with the remaining time reserved to NBS and collaborators. 4 refs.; 3 figs.

RUSH

STUDY OF D₂O ICE AS A COLD-NEUTRON SOURCE

Rush, J.J.; Connor, D.W.; Carter, R.S.

Nuclear Science and Engineering (U.S.) v 25., p. 383-9 (1966).

The leakage flux from an 18 v 18 in. cylinder of D₂O with a beam of pile neutrons incident at its center has been studied at D₂O temperatures from 22° to 293°K. Intensities through beryllium and graphite filters, as well as indium foil transmissions, have been measured to determine cold-neutron fractions and neutron temperatures for the emerging spectra. The results of these measurements show that large volumes of D₂O ice can be useful as low-temperature moderators in reactors. The percentage of leakage neutrons with $\lambda_n \geq 3.95$ Å is 21% at 22°K, a 20-fold increase over the fraction at 293°K, and about twice the value at 100°K. The neutron temperature of the leakage spectrum, calculated from the transmission data assuming a Maxwellian distribution, decreases with moderator temperature, reaching a value of about 75° for D₂O at 22°K. An abrupt increase in the fraction of cold neutrons is observed at the D₂O freezing point, which appears to reflect a change in the transport rather than the moderating properties of the D₂O, due to a decrease in the cross section for long-wavelength neutrons.

RUSSELL

THE LANSCE TARGET SYSTEM

Russell, G.J.; Robinson, H.; Legate, G.L.; Woods, R.; Whitaker, E.R.; Bridge, A.; Hughes, K.J. and Neef, R.D.

LANL and KFA, Julich

Proceedings of ICANS IX p. 177-244, held at Villigen, Swit. 1986

A liquid hydrogen moderator system was installed at the Los Alamos Neutron Scattering Center in 1985. Monte Carlo neutronics calculations for various thickness of liquid hydrogen and various para to ortho ratios are described. The work done during the LANSCE upgrade of 1985 is described. Operating experience with the liquid hydrogen moderator is discussed and further improvements to LANSCE are described. (P.M.B.)

SAHABETTIN

PRODUCTION OF COLD NEUTRONS

Sahabettin, E.

Patent No.: US 3470065. Assignee: (to Sulzer Brothers Ltd.). (1965).

Document Type: Patent

SANDERS

DESIGN OF A COLD-NEUTRON SOURCE FOR THE MIT REACTOR

Sanders, R.C. ; Lanning, D.D.; Thompson, T.J.
Atomic Energy Commission, Washington, D. C.
Trans. Amer. Nucl. Soc. 14: No. 1, 120-1 (1971 June).

A D₂O ice chamber at 20 K to be installed in the thermal column, and cooled by helium gas flow is described. (P.M.B.)

SCHMATZ

THE SCATTERING OF SLOW NEUTRONS

Schmatz, W.; Stiller, H.
Kernforschungsanlage, Juelich,
Kerntechnik 13: No. 12, p. 525-7 (1971 Dec.).

Experimental investigations which can be performed with cold-neutron beams are briefly described. Different ranges of momentum transfer and energy transfer require specialized instruments. (P.M.B.)

SCHOTT

INELASTIC SCATTERING OF SLOW NEUTRONS

Schott, W.
Z. Physik 231, 243 (1970).
Language: German

Para-ortho transitions in solid hydrogen above the lambda-point have been measured by inelastic neutron scattering. From the scattered spectra the widths of the rotational lines caused by the quadrupole-quadrupole interaction between the ortho-molecules are determined. The full width at half intensity is found to be 1.22 ± 0.007 and 0.80 ± 0.07 meV for 68 and 25 percent ortho-concentration respectively in good agreement with theoretical values. The phononspectrum of solid hydrogen could be extracted from the neutron scattering data. The specific heat and the Debye-temperature which were calculated from the phononspectrum are in fairly good agreement with experimental values. Moreover, the double differential scattering cross section of liquid hydrogen ($T=19.8^\circ\text{K}$) was measured at 87 and 21.8 meV incident neutron energy. In the case of 87 meV energy there is a relatively good agreement with a simple free rotator model. At 21.8 meV the binding of the molecules in the liquid influence the spectrum. Therefore a description of the measured spectrum by a convolution of the phononspectrum of the solid and a simple diffusion model was tried. This model is superior to the gas model but discrepancies between model and experiment still remain.

SEARS

THEORY OF COLD NEUTRON SCATTERING BY HOMONUCLEAR DIATOMIC LIQUIDS: I FREE ROTATIONS

Sears, V.F.

AECL

Can. J. Phys. 44, 1279-1297 (1966)

The cold-neutron-scattering cross section for a system of homonuclear diatomic molecules with arbitrary nuclear spin and an arbitrary ortho-para ratio is calculated in first Born approximation, assuming that the molecular rotation is unhindered. The cross section is expressed in the form of an expansion in terms of the angular momentum transfer. This expansion is shown to be rapidly convergent for all the permanent homonuclear diatomic liquids. To the extent that the intermolecular forces are described by an isotropic Lennard-Jones potential, the terms in the expansion can be calculated with the help of the law of corresponding states and the observed scattering functions for the condensed inert gases. The problem of neutron diffraction by homonuclear diatomic liquids is also investigated.

THEORY OF COLD NEUTRON SCATTERING BY HOMONUCLEAR DIATOMIC LIQUIDS: II HINDERED ROTATIONS

Sears, V.F.

AECL

Can. J. Phys. 44, 1299-1311 (1966).

The partial wave expansion of the cold-neutron-scattering cross section for a homonuclear diatomic liquid in terms of the angular momentum transfer, which was introduced in a previous article for the case of free rotation, is generalized to include hindered rotation. The cross section is expressed in terms of an orientational distribution function that is the rotational analogue of the Van Hove self-correlation function. The rotational scattering function for the l th partial wave is shown to be the Fourier transform of a rotational relaxation function, $F(t)$, which is also the l th coefficient of the expansion of the orientational distribution function in terms of spherical harmonics. The functions $F(t)$ are calculated for the limiting cases of free rotation and rotational diffusion. The problem of neutron diffraction by homonuclear diatomic liquids is also investigated, and it is shown that the small angle scattering is determined by the isothermal compressibility. This is a generalization of the well-known result for monatomic liquids.

NEUTRON OPTICS: AN INTRODUCTION TO THE THEORY OF NEUTRON OPTICAL PHENOMENA AND THEIR APPLICATIONS

Sears, V.F.

AECL

Oxford Series on Neutron Scattering in Condensed Matter, V.3. (1989)

ANALYTIC SCATTERING KERNELS FOR NEUTRON THERMALIZATION STUDIES

Sears, V.F.

Report: AECL 10056, Chalk River Nuclear Laboratories, Atomic Energy of Canada Limited.

A simple analytical model for the scattering kernel of monatomic and diatomic liquids is developed. The results of extensive numerical calculations based on this model for liquid hydrogen, liquid deuterium, and mixtures of the two are presented. These calculations demonstrate the dependence of the scattering kernel on the incident and scattered-neutron energies, the behavior near rotational thresholds, the dependence on the center-of-mass pair correlations, the dependence on the ortho concentration, and the dependence on the

deuterium concentration in H_2/D_2 mixtures. The total scattering cross sections are also calculated and compared with available experimental results. 5 tabs.; 29 figs.; 30 refs.

SEIFFERT

MEASUREMENTS OF THE SCATTERING CROSS SECTIONS OF LIQUID AND SOLID HYDROGEN, DEUTERIUM AND DEUTERIUM HYDRIDE FOR THERMAL NEUTRONS

Seiffert, W.D.

EUR 4455 d, p. 36 (1970)

Language: German

English translation ORNL-tr-5153 (1984).

Measurements of the scattering cross sections for thermal neutrons (2 to 80 meV) of liquid and solid normal- H_2 , para- H_2 , D_2 and HD are presented. The scattering by liquid para- H_2 and D_2 shows clearly coherent features. The cross sections of liquid and solid para- H_2 and HD show the onset of inelastic scattering with excitation of the first rotational level. The measured cross sections are compared with numerical calculations.

SEREBROV

A UNIVERSAL SOURCE OF POLARIZED COLD AND ULTRACOLD NEUTRONS AT THE LNPI WWR-M REACTOR

Sevebrov, A.P.

'Weak and electromagnetic interactions in Nuclei', Proceedings.

Berlin (Germany, F.R.). Springer, p. 559-561 (1986).

Published in summary form only

Work Location: Leningrad

SQUIRES

THE SCATTERING OF SLOW NEUTRONS BY ORTHO- AND PARA-HYDROGEN

Squires, G.L.; Stewart, A.T.

Proc. Roy. Soc. A230 19 (1955).

The neutron velocity selector of the Cavendish Laboratory has been used to measure the scattering cross-section of ortho- and para-hydrogen for slow neutrons. The triplet and singlet scattering amplitudes of the neutron proton interaction may be deduced from these cross sections.

SPATH

SAFETY REPORT ON THE COLD NEUTRON SOURCE AT FR2, PROJECT FR2/16

Spath, F.; Karb, E.; Oehme, H.

Kernforschungszentrum, Karlsruhe F.R. West Germany

Language: German.

It is planned to install a cold-neutron source into the horizontal hole R3 of the reactor FR2. This source mainly consists of a moderator chamber to be placed into the reactor reflector

zone. It is filled with 220 cm³ of liquid hydrogen and cooled by gaseous helium in a helium refrigeration system equipped with expansion turbines. An apparatus containing 1 standard cubic metre of gaseous hydrogen feeds the chamber, whilst a vacuum system provides the refrigeration isolation. The background of higher-energetic neutrons is reduced by a neutron filter made of beryllium which is mounted into the beam tube and cooled with liquid nitrogen. In order to avoid a reaction between H₂ and air as well as other conceivable hazards; a number of safety precautions were taken; besides, the hydrogen chamber was surrounded by a pressure tube to protect the reactor core. The experimental facility is automatically controlled from the project control panel. Any trouble will produce an alarm and appropriate measures will be initiated by safety circuits. In special cases the H₂ system is evacuated or the reactor is scrammed. 94 p., 15 figs.; 52 refs.

STELZER

THERMODYNAMIC DESIGN OF THE COLD NEUTRON SOURCE AT THE REACTOR FRJ-2

Stelzer, F.

Kernforschungsanlage, Juelich, F.R. Germany

Kerntechnik 13: No. 12, 534-9 (1971 Dec.).

The nuclear heating at the cold source is taken to be 4.2 W/g in liquid hydrogen and 1.2 W/g in aluminum. Available for heat removal is a cryogenic plant capable of transferring 1500 W using cold helium gas at a mass flow rate of 190 g/s and an inlet temperature of 15 K. A systematic thermodynamic analysis made it possible to find the design concept most suitable for the special conditions involved, and to calculate the operating states to be expected with this design.

STEYERL

NEW DEVELOPMENTS IN COLD AND ULTRACOLD NEUTRON RESEARCH

Steyerl, A.; Malik S.S.

Physica 137B 270-81 (1986).

Work Location: Garching, Grenoble, and Univ. Rhode Island.

The paper contains recent contributions to cold and ultracold neutron physics by groups at Garching and Grenoble, and, in a second part, by a group at the University of Rhode Island. We describe first results in neutron microscopy obtained at the ILL and Garching reactors. Two versions of a two-mirror neutron microscope were used: one employing ultracold neutrons and total-reflecting mirrors, and the other utilizing very cold neutrons in conjunction with multilayer mirrors. We then describe the essential features of the new source of ultracold and cold neutrons which is presently being set up at the HFR, Grenoble, and discuss the novel all-metallic neutron mirrors and guides which were developed in connection with this project. Finally a proposal by the University of Rhode Island for application of high-resolution neutron-optical techniques to the study of critical phenomena in liquids is presented.

A NEW SOURCE OF COLD AND ULTRACOLD NEUTRONS

Steyerl, A.; Nagel, H.; Schreiber, F.X.; Steinhauser, K.A.; Gahler, R.; Glaser, W.; Ageron, P.; Astruc, J.M.; Drexel, W.; Gervais, R.; Mampe, W.
Physics Letters A 116, 347-52 (1986 June).

We report on an intense source of cold and ultracold neutrons at the high-flux reactor at Grenoble: a metal guide conducts neutrons with wavelengths >20 Å from a liquid deuterium cold source to a neutron turbine serving as a generator of a strong and wide beam of ultracold neutrons.

SWAMINATHAN

TRANSPORT OF THERMAL NEUTRONS IN DIFFERENT FORMS OF LIQUID HYDROGEN AND THE PRODUCTION OF INTENSE BEAMS OF COLD NEUTRONS

Swaminathan, K.; Tewari, S.P.

University of Delhi, St. Stephen's College, Delhi, India-110007
Nucl. Sci. Eng. (United States) v 82:2. p. 120-131 (1982 Oct.)

From their studies the authors find that the thermal neutron inelastic scattering kernel incorporating the chemical binding energy in liquid hydrogen is able to successfully explain various neutron transport studies such as pulsed neutron and steady-state neutron spectra. For an infinite-sized assembly, D_2 at 4 K yields a very intense flux of cold and ultracold neutrons. For the practicable finite assembly corresponding to $B^2 = 0.0158 \text{ cm}^{-2}$, it is found that liquid hydrogen at 11 K gives the most intense beam of cold neutrons.

TALHOUK

SCATTERING OF THERMAL NEUTRONS BY LIQUID SOLUTIONS OF ORTHO- AND PARADEUTERIUM

Talhok, S.J.; Harris, P.M.; White, D.; Erickson, R.A.
J. Chemical Physics 48, 1273-1282 (1968).

The structures of two samples of liquid deuterium, one enriched in para-deuterium (85% para- D_2) and the other enriched in orthodeuterium (96.9% ortho- D_2) have been investigated by diffraction of 1-Å neutrons. The scattering data have been interpreted both as an assemblage of atom scatterers and, somewhat more exactly, as molecular scatterers.

TEWARI

ON THE PRODUCTION OF INTENSE BEAMS OF COLD NEUTRONS

Tewari, S.P.; Gangwani, G.S.; Kothari, L.S..
Nucl. Instrum. Methods v. 128 p. 583-584 (1975)
Work Location: India

Theoretical steady-state neutron spectra study on various H_2O - D_2O (ice) mixtures of sample size approximately 0.082 m^3 placed at 21 K in a $1/E$ spectrum, shows that the mixture containing 20% H_2O and 80% D_2O is the optimum for the production of intense beams of cold neutrons.

THEENHAUS

PAST, PRESENT AND FUTURE REACTOR NEUTRON RESEARCH REQUIREMENTS AT THE KERNFORSCHUNGSANLAGE JULICH IN AN INTERNATIONAL CONTEXT

Theenhaus, R; Bauer, G.; Friedewold, H.; Springer, T.; Thamm, G.; Werner, K.
IAEA STI/PUB/762 IAEA-SM-300, 233-243 (1988).

In order to secure and possibly improve the supply of neutrons at the Kernforschungsanlage Julich in the medium term future, refurbishment concepts for FRJ-2 are being studied which range from simple replacements of older parts to a complete exchange of the whole reactor block and use of a new core concept to improve the flux level as well as to reduce the high energy neutron contamination in the thermal and cold beams.

TODD

COLD NEUTRON SOURCE ON A 5-MW POOL REACTOR

Todd, M.C.J.

Atomic Weapons Research Establishment, UK

Conference: Symposium on irradiation facilities for research reactors

Publ: International Atomic Energy Agency, Vienna, STI/PUB/316, 261-269 (1973).

Operating at the HERALD reactor in Aldermaston, the cold source uses a mixture of liquid hydrogen and deuterium. The reactor is a light-water-moderated pool reactor that is normally operated at 5 MW. To allow the installation of the source, space was provided by removing the centre section of one of the two tangential beam tubes. After cutting the beam tube, end caps were welded over the open ends so that the source chamber could be suspended within the reactor tank and located between the two end caps. This arrangement has the advantages that cold neutrons are fed to two beam tubes, but has the disadvantage that the end caps attenuate the neutron current. A hydrogen refrigerator is used to cool the source chamber and was chosen on the grounds of economy. The source and refrigerator systems are separate so that the mixture of hydrogen and deuterium in the source can be varied. The choice of a hydrogen refrigerator has allowed a compact heat exchanger to be designed that is located above the source chamber so that heat is removed by natural convection circulation of the hydrogen-deuterium mixture. The hydrogen refrigerator is located outside the reactor hall and is connected to the heat exchanger by a long transfer line. The volume of the source chamber was limited by the space available in the vicinity of the beam tubes. The first chamber tested had a volume of 5 litres and the second 3 litres. By varying the hydrogen-deuterium mixture it has been shown that the cold neutron current passes through a maximum. The variation has not however, been as great as expected and it is now considered that a small hydrogen-filled source placed as close as possible to the reactor core would provide higher cold neutron currents. With the present 3-litre source the current of thermal neutrons into the source was made as large as possible by surrounding the source chamber by a reflector tank filled with heavy water, and by placing two beryllium filter sections in the source chamber in line with the beam tubes.

TUNKELO

CONSTRUCTION AND PERFORMANCE OF A COLD NEUTRON SOURCE

Tunkelo, E.

Inst. of Tech., Otaniemi, Finland

Acta Polytech. Scand., Phys. Nucl. Ser. v No. 38., p. 1-48, (1966).

The description is presented of a cold-neutron source installed in a tangentially piercing beam tube of the FiR 1 reactor of Institute of Technology, Otaniemi. The moderator chamber is given a "black body radiator"-like geometry in order to enhance the moderation of neutrons. The coolant is separated from the moderator to enable use of different liquids as moderator and coolant. The influence of the moderating material and temperature as well as of the shape and size of moderator is discussed. Cryogenic and safety considerations are also presented. The performance of the cold-neutron source is given in terms of the intensities and spectra of emerging neutrons. Methane (at 78°K) and liquid hydrogen (at 20°K) are used as moderators giving an intensity of $6.7 \cdot 10^6$ neutrons/sec and $1.3 \cdot 10^7$ neutrons/sec for the beryllium filtered beam $3 \times 4 \text{ cm}^2$. 9 tabs.; 22 figs.; 24 refs.

THE COLD NEUTRON FACILITY AT THE FiR 1

Tunkelo, E.; Palmgren, A.

Technical Univ. of Helsinki

Nucl. Instrum. Methods, 46, 266-74 (1967).

A description is given of the cold neutron facility at the FiR 1 (Triga Mark II, 100 kW). The facility utilizes a refrigerated moderator (methane at 77 K) in a tangential beam tube traversing the graphite reflector of the reactor. The beryllium filtered neutron beam is chopped before reaching the sample. The detectors are mounted on movable arms allowing scattering angles between 0° and 130° to be studied. The performance of the facility is characterized by a beryllium filtered cold neutron intensity of 6×10^6 /sec with a beam of $30 \times 40 \text{ mm}^2$, combined with a very low room background. Results of a representative measurement are given.

TURGUT

OPTIMIZATION OF A COLD NEUTRON SOURCE AT THE FRG-1

Turgut, M.H.

GKSS-Forschungszentrum Geesthacht G.m.b.H., Geesthacht-Tesperhude (Germany, F.R.)

GKSS-83/E/37, 67 p. (1983).

This paper describes the optimization of a cold neutron source (CNS) for maximizing the subthermal flux in the energy range 2.27-5.12 meV at the beam tube of FRG-1 reactor. In addition, the gain by using different reflectors (H_2O , C, D_2O) around the CNS is discussed. Advantage factors (resulting from the use of CNS) are calculated for various configurations by means of the transport code NEUTRA. The cross-sections for NEUTRA are prepared by the spectral code GGC-4.

COUPLED DIFFUSION-TRANSPORT COMPUTATIONAL METHOD AND ITS APPLICATION FOR THE DETERMINATION OF SPACE DEPENDENT ANGULAR FLUX DISTRIBUTIONS AT A COLD NEUTRON SOURCE (BRIDGE)

Turgut, M.H.

GKSS-Forschungszentrum Geesthacht G.m.b.H., Geesthacht-Tesperhude (Germany, F.R.); Hamburg Univ. (Germany, F.R.). Fachbereich Physik
GKSS-85/E/8, 129 p. (1985).

A fast calculation program BRIDGE was developed for the calculation of a Cold Neutron Source (CNS) at a radial beam tube of the FRG-I reactor, which couples a total assembly diffusion calculation to a transport calculation for a certain subregion. For the coupling flux and current boundary values at the common surfaces are taken from the diffusion calculation and are used as driving conditions in the transport calculation. Equivalence Theory is used for the transport feedback effect on the diffusion calculation to improve the consistency of the boundary values. The optimization of a CNS for maximizing the subthermal flux in the wavelength range 4 - 6 Å is discussed.

UTSURO

EXPERIMENTAL STUDY ON A COLD NEUTRON SOURCE OF SOLID METHYLBENZENE

Utsuro, M.; Sugimoto, M.; Fujita, Y. (Kyoto Univ., Kumatori, Osaka (Japan). Research Reactor Inst.)

Annu. Rep. Res. Reactor Inst., Kyoto Univ. (Japan) v 8. p. 17-22 (1975 Oct.).

An experimental study to produce cold neutrons with low temperature solid mesitylene as cold moderator in liquid helium and liquid nitrogen cryostats is reported. Measured cold neutron spectra by using an electron linac and time-of-flight method shows that this material is a better cold moderator than light water ice, giving the cold neutron output not so much inferior to that of solid methane in the temperature range above about 20 K and in the neutron energy region above about 1 meV.

SLOW NEUTRON SCATTERING AND INTERMOLECULAR EXCITATIONS IN LIQUID HYDROGEN

Utsuro, M.

Z. Physik B27, p. 111-116 (1977)

A simple analytical model for inelastic neutron scattering in liquid hydrogen with the effects of delayed diffusion and intermolecular vibrations with a single-frequency parameter is proposed. Calculated results show good agreement with experimental results of total and differential scattering cross sections as well as the energy spectra of neutrons in liquid-hydrogen moderators, and thus indicate the importance of the consideration of intermolecular excitations in the dynamics of liquid hydrogen.

LIQUID ORTHO-DEUTERIUM AS A CONVERTER FOR ULTRA-COLD NEUTRONS

Utsuro, M. (Kyoto Univ., Kumatori, Osaka (Japan). Research Reactor Inst.

Hetzelt, M. (Institut Max von Laue - Paul Langevin, 38 - Grenoble (France))

Neutron inelastic scattering 1977. Vol. 1

Publ. IAEA, STI/PUB/468

IAEA-SM-219/63 v.1 p. 67-75 (1978).

Theoretical calculations of UCN gain factors of liquid ortho- and para-deuterium are performed, taking into account the effects of intermolecular interferences and liquid

dynamics in deuterium. Calculated results of UCN production and total cross-sections give very different values from those based on the gas model. The calculation gives a UCN gain factor of 100 for a liquid ortho-deuterium converter if used in combination with a Maxwellian neutron spectrum of 50K. An experiment to measure the UCN gain factor of liquid ortho-deuterium at 20K was carried out. The experimental gain factor is about 3 times larger than the value calculated on the basis of the gas model and in good agreement with the result of the present calculation.

REACTOR COLD NEUTRON SOURCE FACILITY, THE FIRST IN JAPAN

Utsuro, Masahiko; Maeda, Yutaka; Kawai, Takeshi; Tashiro, Tameyoshi; Sakakibara, Shoji; Katada, Minoru
Kyoto Univ., Kumatori, Osaka, Japan. Research Reactor Inst.
Genshiryoku Kogyo (Japan) v 32:1. p. 51-58, (1986 January).
Language: Japanese.

In the Research Reactor Institute, Kyoto University, the first cold neutron source facility for the reactor in Japan was installed, and various tests are carried out outside the reactor. Nippon Sanso K.K. had manufactured it. After the prescribed tests outside the reactor, this facility will be installed soon in the reactor, and its outline is described on this occasion. Cold neutrons are those having very small energy by being cooled to about 250 deg. C. Since the wavelength of the material waves of cold neutrons is long, and their energy is small, they are very advantageous as an experimental means for clarifying the structure of living body molecules and polymers, the atom configuration in alloys, and atomic and molecular movements by neutron scattering and neutron diffraction. The basic principle of the cold neutron source facility is to irradiate thermal neutrons on a cold moderator kept around 20 K, and to moderate and cool the neutrons by nuclear scattering to convert to cold neutrons. The preparatory research on cold neutrons and hydrogen liquifaction, the basic design to put the cold neutron source facility in the graphite moderator facility, the safety countermeasures, the manufacture and quality control, the operation outside the reactor and the performance are reported. The cold neutron source facility comprises a cold moderator tank and other main parts, a deuterium gas tank, a helium refrigerator and instrumentation.

LIQUID DEUTERIUM COLD SOURCE IN GRAPHITE THERMAL COLUMN

Utsuro M.; Kawai, T.; Maeda, Y.; Yamaoka H.; Akiyoshi T.; and Okamoto, S
Kyoto University, Osaka Japan
Physica B 156/157 p. 540-543 (1989).

A liquid deuterium cold source with a non-spherical moderator chamber of about 4 litres was installed into the graphite thermal column of 5 MW Kyoto University Reactor (KUR). Three cold neutron holes and one very cold neutron hole are provided in the graphite for beam extractions. The operation tests with hydrogen liquefied in the condenser showed satisfactory performances and high gain factors of cold and very cold neutrons of more than 20 and 10, respectively. Neutron measurements with the deuterium moderator are now in progress.

A COMBINED SYSTEM FOR THE GENERATION OF AN INTENSE COLD NEUTRON BEAM WITH A MEDIUM POWER RESEARCH REACTOR

Utsuro, M.; Okumura, K.
Kyoto University, Osaka (Japan).
Nuclear Instruments and Methods in Physics Research, A:281:3. p. 649-651 (1989 September).

A system consisting of a very cold moderator and a neutron-accelerating high speed turbine is proposed for the intensification of a cold neutron beam in a medium power research

reactor up to the level applicable to inelastic neutron scattering spectrometers. A numerical result for 5 cm thick solid ortho-deuterium at a temperature of about 4 K and a turbine with a blade velocity of about 350 m/s gives an output intensity of monochromatic neutrons of about 10^7 n/cm² at an energy of about 3.5 meV with an energy width of about 0.2 meV for a typical case of a 5 MW reactor.

VALO

STUDY OF A COLD NEUTRON SOURCE

Neutron inelastic scattering 1977. Vol. 1

Valo, M.J. (Valtion Teknillinen Tutkimuskeskus, Otaniemi (Finland)

Reaktorilaboratorio)

Publ: IAEA, STI/PUB/468

IAEA-SM-219/10 p. 78-85 (1978).

A hydrogen cold neutron source has been constructed allowing wide variation of density, temperature and ortho-hydrogen concentration. The maximum cold neutron flux was obtained with para-rich hydrogen at the lowest temperature attained. Substitution of normal hydrogen by parahydrogen doubled the cold neutron flux. The effect of density and ortho-concentration is explained qualitatively.

VAN DINGENEN

SYSTEMATIC STUDY OF COLD NEUTRON SOURCES

Van Dingenen, W.; Hautecler, S.

Brussels. Centre d'Etude de l'Energie Nucleaire

NP-9548, p. 31 (1960).

Presented at the International Atomic Energy Agency Symposium on Inelastic Scattering of Neutrons in Solids and Liquids, 1960 October 11-14.

See also Hautecler

Language: English

Research is described which was to study and evaluate the factors on which the yield of a cold neutron source depends. The temperature, dimensions, and chemical nature of the moderator are the parameters involved. It was found that the moderation consists in an integral displacement of the thermal neutron spectrum toward the low energies; the shape of the spectrum is only slightly changed. The average apparent temperature of neutrons decreases almost linearly with moderator temperature. An absorber in the moderator displaces the spectrum toward higher energies and at the same time lowers the total flux by an exponential factor. For a moderator with good slowing-down power the spectrum shows only cooling and no intensity increase up to a very definite volume. Displacement of the spectrum by moderation depends on the chemical nature of the moderator. (T.R.H.)

SYSTEMATIC STUDY OF SOME COLD-NEUTRON SOURCES

Van Dingenen, W.

Centre d'Etude de l'Energie Nucleaire, Mol, Belgium

Nuclear Instr. & Methods v 16., p. 116-28 (1962 June).

Systematic measurements of apparent neutron temperatures and of energy spectra are made for neutrons slowed down by small amounts of hydrogenous moderating materials, cooled

to liquid nitrogen and liquid hydrogen temperatures. Some qualitative conclusions are drawn about the moderation phenomena at very low temperatures.

TOTAL CROSS SECTION FOR SCATTERING OF COLD NEUTRONS BY PROTONS IN SOME COOLED HYDROGENOUS COMPOUNDS

Van Dingenen, W.; de Mevergnies, M.N.
Centre d'Etudes Nucleaires, Mol. Belg.
Physica 30, p. 237-43, (1964 Jan).

Total neutron cross sections have been measured for some hydrogenous compounds (acetylene, ammonia, methane) condensed at different low temperatures, and for neutron wavelengths between 1 Å and 12 Å. From the variation of the neutron cross section as a function of temperature and neutron wavelength some information is derived about the dynamical behaviour of the bound protons. An interpretation of the results is tried in terms of an effective Debye temperature characterizing each moderator. For solid ammonia the Debye-model fits rather well, but for methane it seems inadequate. There appears to be a good correlation between the values obtained for the inelastic scattering cross section, and the results of earlier measurements on the output of cold-neutron sources.

WATANABE

PRELIMINARY OPTIMIZATION EXPERIMENTS OF COUPLED LIQUID HYDROGEN MODERATORS FOR KENS-II

Watanabe, N.; Kiyanagi, Y.; Inoue, K.; Furusaka, M.; Ikeda, S.; Iwasa, H.
Proc. ICANS X, p. 787-797 (1988 October 3-7)

WEBB

PROPOSED LIQUID HYDROGEN MODERATOR IN DIDO

Webb, F.J.
AERE NP/R 2547 (1958 May)

COLD NEUTRON BEAMS FROM SMALL LOW-TEMPERATURE MODERATORS IN REACTORS

Webb, F.J.
AERE, Harwell
Nucl. Sci. Eng. 9, 120-126 (1961)

An investigation has been made of the efficiency of several hydrogenous low-temperature moderators in the production of intense cold-neutron beams from reactors. The dimensions of such a moderator are usually severely limited, but even small volumes of liquid hydrogen, liquid hydrogen deuteride, and solid methane were effective. A qualitative theoretical explanation is given of the degree of moderation observed.

COLD NEUTRON SOURCES

Webb, F.J.
Atomic Energy Research Establishment, Harwell, Berks, Eng.
J. Nucl. Energy, Pt. A & B v 17., p. 187-215 (1963 July).

Experimental work on cold neutron source development is reviewed along with the theoretical explanations devised for the results obtained. Factors governing source design,

the associated cryogenic and safety problems, large source design, and experiments by which source efficiency might be increased are also discussed. (D.C.W.)

WHITTEMORE

DIFFERENTIAL NEUTRON THERMALIZATION

Whittemore, W.L.
GA-7439, (1967).

YOUNG

SLOW NEUTRON SCATTERING BY MOLECULAR HYDROGEN AND DEUTERIUM

Young, J.A.; Koppel J.U.
Physical Review 135, p. A603-11 (1964).

The cross sections for neutrons scattering from H_2 and D_2 have been calculated taking into account the spin correlations, rotations, and vibrations of the molecules exactly, to the extent that the vibrations are harmonic and do not interact with the rotations. Free translations of the molecules are assumed, but this assumption is expected to be valid in the liquid, as well as the gas, for neutron energies above 0.007 eV, the Debye temperature for hydrogen. Numerical results are given for the total cross section for both orthohydrogen and parahydrogen gas at 20.4°K which agree reasonable well with the limited experimental results available. Also curves of the double differential cross section are shown for selected incident neutron energies and scattering angles. These latter curves show very clearly the various rotational and vibrational transitions. The formulas given here are applicable at all temperatures below the thermal excitation of the first vibrational level.

DESIGN AND CONSTRUCTION OF A COLD NEUTRON SOURCE FOR USE IN THE CORNELL UNIVERSITY TRIGA REACTOR

Young, L.J.
Thesis (Ph. D.), p. 136 (1983).
Availability: University Microfilms Order No. 83-09, 434.

A cold neutron source has been designed and constructed for insertion into the 6-inch radial beam port of the Cornell University TRIGA reactor for use with a neutron guide tube system. The main differences between this cold source and other existing sources are the use of heat conduction as the method of cooling and the use of mesitylene (1,3,5-trimethylbenzene; melting point, 228 K; boiling point, 437 K) as the moderating material. This thesis describes the design and construction details of the cold neutron source, discusses its safety aspects, and presents its cryogenic performance curves and also the results of a test of its neutron moderating ability. To test the neutron moderating ability of the cold neutron source, an out-of-reactor neutron transmission experiment was performed with the moderator chamber first at room temperature and then at about 23 K. The results indicate that the neutron energy spectrum is strongly shifted to lower energies when the chamber is cold. The neutrons have an apparent temperature of 98 K, if the moderated flux is assumed to be Maxwellian. This, however, is unlikely to be the actual case since the geometry of the chamber, neutron beam, and detector and the complexities of the neutron scattering and absorption processes in mesitylene doubtlessly distort the leakage energy spectrum.

DESIGN AND TEST OF A CRYOGENIC SYSTEM FOR A COLD NEUTRON SOURCE FOR THE CORNELL TRIGA REACTOR

Young, L.J.; Clark, D.D.

Cornell University, Ithaca NY

Atomkernenergie Kerntechnik Supplement to V 44, p. 383-8, (1984).

A test model of a cryogenic system is described for a proposed cold-neutron source for a curved neutron guide tube being installed at the Cornell University TRIGA reactor. Designed for insertion into a six-inch diameter beam port, its distinctive features include the use of heat conduction in copper as the method of cooling and the use of mesitylene (1,3,5-trimethylbenzene) as the cold moderator. Design, construction, and safety aspects are discussed. The system has not yet been tested in the beam port, but out-of-reactor tests are described in which temperatures as low as $24\pm 3^\circ\text{K}$ were reached and the apparent temperature of an incident thermal neutron beam was reduced to 98°K . Conversion of the test model into final form for actual use is in progress.

ZSIGMOND

COLD NEUTRON SOURCE AT THE BUDAPEST WWR-SM REACTOR

Zsigmond, Gy.; Barth, P.; Cser, L.; Rosta, L.; Szalok, M.

Hungarian Academy of Sciences, Budapest. Central Research Inst. for Physics

Report No.: KFKI-1988-49/E 35 p. 1988 October.

Upgrading and complete reconstruction of the KFKI WWR-SM reactor includes the installation of a cold neutron source in order to improve neutron scattering facilities for condensed matter research. The principles of cold neutron moderators are given, and the operation as well as the main elements of a small size cell liquid hydrogen cold source planned to be installed are presented describing also the installation and testing procedures. The most important hazard factors and safety problems are analyzed. (author)

Index for Appendix A

- Ageron, P. 614
Altarev, I. S. 616
Antonov, A. V. 616
Azmy, Y. Y. 616
Basu, S. 617
Bauer, G. 617
Bernnat, W. 618
Buchholz, H. Von 618
Butterworth, I. 619
Carneiro, K. 619
Carter, P. 619
Cocking, S. J. 620
Dahlborg, U. 620
Dimic, V. 621
Doose, C. 621
Egelstaff, P. A. 622
Elliott, R. J. 622
Galotto, C. P. 623
Gangwani, G. S. 623
Granada, J. R. 623
Hagen, H. 624
Harig, H. 624
Hautecler, S. 625
Henderson, D. L. 625
Hoffman, H. 626
Inoue, K. 627
INSPEC 627
Jacrot, B. 628
Jensen, K. 628
Jinghui, R. 629
Kalli, H. 629
Kawabata, Y. 630
Kawai, T. 630
Keinert, J. 631
Kevey, A. 631
Koepppe, W. 632
Konoplev, K. A. 632
Koppel, J. U. 632
Kottwitz, D. A. 632
Kraehling, E. 633
Krueger, A. 633
Krull, W. 634
Kumai, T. 634
Leth, J. A. 635
Lillie, R. A. 635
Lovseth, J. 635
MacFarlane, R. E. 636
Merrett, D. J. 636
Michaudon, A. 636
Moon, J. R. 636
Neef, R. D. 637
Nielsen, J. 637
Olivi, L. 637
Onishi, N. 637
Pearce, D. G. 638
Persson, P. 639
Preussner, A. 639
Rief, H. 639
Ritenour, R. L. 640
Rogov, A. D. 640
Rowe, J. M. 640
Rush, J. J. 641
Russell, G. J. 641
Sahabettin, E. 641
Sanders, R. C. 642
Schmatz, W. 642

Schott, W. 642
Sears, V. F. 643
Seiffert, W. D. 644
Serebrov, A. P. 644
Squires, G. L. 644
Spath, F. 644
Stelzer, F. 645
Steyerl, A. 645
Swaminathan, K. 646
Talhouk, S. J. 646
Tewari, S. P. 646
Theenhaus, R. 647
Todd, M. C. J. 647
Tunkelo, E. 648
Turgut, M. H. 648
Utsuro, M. 649
Valo, M. J. 651
Van Dingenen, W. 651
Watanabe, N. 652
Webb, F. J. 652
Whittemore, W. L. 653
Young, J. A. 653
Zsigmond, G. 654

Appendix B

Questions to be Addressed at the International Workshop on Cold Neutron Sources

The review talks are meant to bring everyone to the same general knowledge of existing cold sources at reactor and spallation installations worldwide. The review presentations will address design criteria, design, fabrication, operation, safety, instrumentation and monitoring, and performance. The formal workshop talks will provide overviews of a pertinent topic and will be slanted toward providing answers to the following questions:

Neutronics Calculations:

- What are the best cross section sets to use
 - What validation/verification of them is available
 - Where are they documented
 - Where do we get the latest scattering kernels; how to measure; for what materials
- What kerma factor sets are available
 - What validation/verification of them is available
 - Where are they documented
- What codes and techniques are used for neutronics and thermalization calculations
 - What validation/verification of them is available
 - Where are they documented
 - Which techniques are applicable where
 - Simplified approaches
 - Advantages/Pitfalls in the use of Monte Carlo techniques
- Design and optimization criteria for cold sources
 - Parametric descriptions
 - How much detail is necessary
 - Ortho-hydrogen versus para-hydrogen as a moderator
 - Ortho-deuterium versus para-deuterium as a moderator
 - Hydrogen/deutrium mixtures
 - Deuterium versus hydrogen
 - Natural and deuterated methane
 - Composite moderators
 - Other moderator materials
 - Optimum moderator sizes, reentrant geometry, vessel shape, etc.

- Source characterization (fitting neutron spectra and pulse widths)

Heating:

- Estimated heating rates
 - How well are they known
 - What calculational techniques are available for thermal design of cold sources
 - Where are the computational tools documented
 - What experimental data are available to verify calculational approaches
 - What's more important, neutrons or gamma rays; origin of cold source heating
 - Composite moderators
- Heat removal
 - What are the limiting factors on heat removal capability for different cold source designs
 - Are all the necessary physical properties for moderators and other materials available; if so where
 - Thermosyphon system design
 - Cryogenic liquid pumping system design

Instrumentation and Control:

- What parameters (temperature, liquid level, neutron flux, heat load, etc.) do we need to measure; how are such measurements made
- How can we best control cold source temperature, liquid level, thermo-hydraulic stability, etc.
- What control links are needed between the thermal neutron source (reactor or accelerator and moderator) and the cold source

Materials, Mechanical Design, and Fabrication:

- What materials properties at low temperature are available
 - Where are they documented
 - Material strengths
 - Importance of phase transitions
 - Weldability
- What data are available on irradiation effects, especially on slow neutron effects at low temperature and on annealing effects
 - Where is such information documented
 - Corrosion
 - Cold source lifetime

- Change in mechanical properties
- Methane (solid and liquid) radiation damage and resulting operational constraints
- What are the additional radiation damage concerns at a spallation source compared to a reactor
- What design criteria (nominal criteria, confinement criteria, safety margins, off-normal operation, etc.) are appropriate for cold sources
- What fabrication techniques are proven for low temperature operation and thermal cycling in a high-gamma and slow-neutron flux
- Cold Source testing
 - Neutronic studies
 - Heat removal
 - Engineering aspects
 - Radiation damage
 - Methane moderator "burping" phenomena

Future Cold Sources:

- New moderator and structural materials
- New scattering kernels
- Novel moderator designs; composite moderators
- Are the correct approaches being followed in the New Cold Neutron Source Proposals

Appendix C

Attendees List for the International Workshop on Cold Neutron Sources

March 5-7, 1990

Dr. Paul Ageron
Institute Laue Langevin
156X
38042 Grenoble Cedex
FRANCE
Phone: 011-33-7648-7111
FAX: 011-33-7648-3906

Dr. R. G. Alsmiller, Jr.
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37830
Phone: 615-574-6081
FAX: 615-576-2760

Dr. Paul Breant
CEN Saclay
SPS ORPHEE
91191 Gif-sur-Yvette Cedex
FRANCE
Phone: 011-33-1-6908-4611
FAX: 011-33-1-6908-8320

Art Bridge
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-6069
FAX: 505-665-2676

Dr. David D. Clark
Cornell University
Ward Laboratory
Ithaca, NY 14853-7701
Phone: 607-255-5224
FAX: 607-255-9417

Dr. David Alexander
Oak Ridge National Laboratory
4500 S. MS 6151
P.O. Box 2008
Oak Ridge, TN 37831
Phone: 615-574-4467
FAX: 615-574-5118

Dr. Gunter S. Bauer
Paul Scherrer Institute
CH-5234
Villigen
SWITZERLAND
Phone: 011-41-56-99-2524
FAX: 011-41-56-98-2327

Dr. Peter M. Brewster
Atomic Energy of Canada, Ltd
Chalk River Nuclear Labs
Chalk River, ONT KOJ 1JO
CANADA
Phone: 613-584-3311
FAX: 613-584-4024

Dr. Torben Brun
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-8841
FAX: 505-665-2676

Debbie Clark
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-3079
FAX: 505-665-2676

Don Alger
Research Reactor Facility
University of Missouri-Columbia
Research Park
Columbia, MO 65211
Phone: 314-882-5229
FAX: 314-882-3443

Dr. Wolfgang Bernnat
University of Stuttgart
IKE
Postfach 801140
D-700 Stuttgart-80
WEST GERMANY
Phone: 011-49-711-685-2118
FAX: 011-49-711-685-2010

Roland Brewton
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-3886
FAX: 505-665-2676

Dr. Jack M. Carpenter
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439
Phone: 708-972-5519
FAX: 708-972-4163

Dr. Kurt N. Clausen
RISO National Laboratory
Physics Department
Postbox 49
DK-4000 Roskilde
DENMARK
Phone: 011-45-42-371212
FAX: 011-45-42-370115

Dr. John Conant
WX-5, MS G780
Los Alamos National Lab
Los Alamos, NM 87545
Phone: 505-667-8035
FAX: 505-667-9582

Cliff Eberle
Oak Ridge National Laboratory
Bldg. 9204-01, MS 8053
P.O. Box 2009
Oak Ridge, TN 37831-8053
Phone: 615-576-7241
FAX: 615-574-2323

Takshi Emoto
University of Texas at Austin
Nuclear Engineering Teaching Lab
10100 Burnet Road
Austin, TX 78758
Phone: 512-471-5787
FAX: 512-471-4589

Dr. Walter E. Fischer
Paul Scherrer Institute
CH-5234 Villigen
SWITZERLAND
Phone: 011-41-56-99-3412
FAX: 011-41-56-99-3294

Allan Gjovig
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-3886
FAX: 505-665-2676

Robert Haight
P-15, MS D406
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-2829
FAX: 505-667-0401

Dr. Helmut Hoffman
KFK Karlsruhe GmbH
Institute Für Reaktorbauelemente
Postfach 3640
D-7500 Karlsruhe
WEST GERMANY
Phone: 011-49-7247-82-3473
FAX: 011-49-7247-82-5070

Gary Cooper
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-4074
FAX: 505-665-2676

Juergen Eckert
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-2374
FAX: 505-665-2676

Dr. B. Farnoux
CEN Saclay
Laboratoire Léon Brillouin
91191 Gif-sur-Yvette Cedex
FRANCE
Phone: 011-33-69-08-2635
FAX: 011-33-1-69-08-8261

Wayne Frazer
Headquarters NASA
Code QSO
600 Independence Ave. SW
Washington, DC 20546
Phone: 202-453-8910
FAX: 202-426-0383

Dr. Klaus Gobrecht
Institute Laue Langevin
156X
38042 Grenoble Cedex
FRANCE
Phone: 011-33-7648-7042
FAX: 011-33-7648-3906

Dr. William Hamilton
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-6069
FAX: 505-665-2676

Dianne K. Hyer
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-8950
FAX: 505-665-2676

Steve Donahue
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-4075
FAX: 505-665-2676

Professor Peter A. Egelstaff
University of Guelph
Department of Physics
Guelph, ONT N1G 2W1
CANADA
Phone: 519-824-4120
FAX: 519-836-9967

Dr. Carl O. Fischer
Hahn-Meitner-Inst. Berlin GmbH
Project KNQ
Postfach 390128
D-1000 Berlin 39
WEST GERMANY
Phone: 011-49-30-8009-2746
FAX: 011-49-30-8009-2999

Dr. Michihiro Furusaka
National Laboratory for
High Energy Physics
1-1 Oho-machi, Tsukuba-shi
Ibaraki-ken 305
JAPAN
Phone: 011-0298-64-1171
Ext. 3627
FAX: 011-0298-64-3202

Dr. Joyce A. Goldstone
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-3626
FAX: 505-665-2676

Dr. Rex P. Hjelm
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-2372
FAX: 505-665-2676

Dr. Takeshi Kawai
Kyoto University
Research Reactor Institute
Kumatori-cho, Sennan-gun
Osaka 590-04
JAPAN
Phone: 011-81-724-52-0901
FAX: 011-81-724-53-1043

Ewald Krahling
Technische Universität München
Fakultät f. Physik E21
James-Frank-Str.
D-8046 Garching
WEST GERMANY
Phone: 011-49-89-3209-2122
FAX: 011-49-89-3209-2112

Dr. Albert G. Lee
Atomic Energy of Canada, Ltd
Witeshell Nuclear Research
Establishment
Pinawa, Manitoba
R0E 1L0
CANADA
Phone: 204-753-2311
FAX: 204-753-2455

Dr. Robert C. Little
X-6, MS B226
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-4189
FAX: 505-665-5538

Dr. Robert MacFarlane
T-2 ANS, MS B243
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-7742
FAX: 505-667-9671

Dr. Ross Miller
ANS Project
Oak Ridge National Laboratory
FEDC Building, MS 8218
P.O. Box 2009
Oak Ridge, TN 37831-8218
Phone: 615-576-5427
FAX: 615-576-5436

Murlin J. Nutter
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-2935
FAX: 505-665-2676

Dr. Wilfried Krull
GKSS
Postfach 1160
D-2054 Geesthacht
WEST GERMANY
Phone: 011-49-4152-87-1200
FAX: 011-49-4152-87-1338

Gail Legate
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-3191
FAX: 505-665-2676

Kathy Jo Lovell
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-3078
FAX: 505-665-2676

Dr. S. S. Malik
University of Rhode Island
Department of Physics
108 East Hall
Kingston, RI 02881-0817
Phone: 401-792-2633
FAX: 401-792-2380

Dr. Fred Morse
ADR, MS A114
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-1600
FAX: 505-665-3858

Dr. Eric H. Ottewitte
Idaho National Engineering Lab
P.O. Box 1625
Idaho Falls, ID 83415-2211
Phone: 208-526-1751
(FTS 583-1751)
FAX: 208-526-2814
(FTS 583-2814)

Dr. Allen C. Larson
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-2942
FAX: 505-665-2676

Dr. Richard A. Lillie
Oak Ridge National Laboratory
Building 6025
P.O. Box 2008
Oak Ridge, TN 37831-6364
Phone: 615-574-6083
FAX: 615-576-2760

Dr. J. Eric Lynn
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-4047
FAX: 505-665-2676

J. Charles McKibben,
Associate Director
Research Reactor Facility
University of Missouri-Columbia
Research Park
Columbia, MO 65211
Phone: 314-882-5204
FAX: 314-882-3443

Dr. Ron Nelson
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-0394
FAX: 505-665-2676

Dr. Richard E. Prael
X-6, MS B226
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-7283
FAX: 505-665-5538

Dr. Roger Pynn
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-8842
FAX: 505-665-2676

Dr. R. A. Robinson
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-3626
FAX: 505-665-2676

Kathy F. Rosenbalm
Advanced Neutron Source Project
Oak Ridge National Laboratory
Fusion Engineering Design Center
P.O. Box 2009
Oak Ridge, TN 37831-8218
Phone: 708-574-0558
(FTS 624-0558)
FAX: 708-576-3041
(FTS 626-3041)

Dr. Terry Scott
Argonne National Laboratory
IPNS
9700 S. Cass Avenue
Argonne, IL 60439
Phone: 708-972-6799
FAX: 708-972-4163

Dr. Richard Silver
T-2 ANS, MS B262
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-1166
FAX: 505-667-9671

Dr. Tasso Springer
Institute Für Festkörperforschung
Kernforschungsanlage Jülich GmbH
Postfach 1913
D-5170 Jülich
WEST GERMANY
Phone: 011-2461-61-4699
FAX: 011-49-2461-61-2410

Thomas Rieker
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-2373
FAX: 505-667-2676

Dr. Hans-Joachim Roegler
Interatom GmbH
Frederich Ebert Strasse
D-5060 Bergisch-Gladbach 1
WEST GERMANY
Phone: 011-49-2204-84-4681
FAX: 011-49-2204-84-2207

Dr. J. Michael Rowe
National Institute of Standards
and Technology
Gaithersburg, MD 20899
Phone: 301-975-6210
FAX: 301-921-9847

Dr. Varley Sears
Atomic Energy of Canada, Ltd
Chalk River Nuclear Laboratories
Chalk River, ONT K0J 1J0
CANADA
Phone: 613-584-3311
FAX: 613-584-4024

Dr. Gregory S. Smith
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-665-2842
FAX: 505-665-2676

Dr. Erich Steichele
Physik Department E21
Technische Universität München
D-8046 Garching
WEST GERMANY
Phone: 011-49-89-3209-2141
FAX: 011-49-89-3209-2112

Dr. Harold Robinson
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-2072
FAX: 505-665-2676

Dr. Dave Rorer
Brookhaven National Laboratory
Reactor Division, Bldg. 750
75 Cornell Street
Upton, NY 11973
Phone: 516-282-4056
FAX: 516-282-2560/2619

Dr. Gary Russell
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-2937
FAX: 505-665-2676

Dr. Phil A. Seeger
LANSCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-8843
FAX: 505-665-2676

Dr. Walter F. Sommer
MP-5, MS H838
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-1269
FAX: 505-665-1712

Dr. Eric Svensson
Atomic Energy of Canada, Ltd
Chalk River Nuclear Laboratories
Chalk River ONT K0J 1J0
CANADA
Phone: 613-584-3311 Ext. 3992
FAX: 613-584-4040

Dr. Masahiko Utsuro
Kyoto University
Research Reactor Institute
Kumatori-cho, Sennan-gun
Osaka 590-04
JAPAN
Phone: 011-81-724-52-0901
FAX: 011-81-724-53-8149

Robert Von Dreele
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-3630
FAX: 505-665-2676

Dr. Colin West
Advanced Neutron Source Project
Oak Ridge National Laboratory
Fusion Engineering Design Center
P.O. Box 2009
Oak Ridge, TN 37831-8218
Phone: 615-574-0370
(FTS 624-0370)
FAX: 615-576-3041
(FTS 626-3041)

Dr. Jacques Verdier
Centre d'Etudes Nucleaires
SBT
38041 Grenoble Cedex
FRANCE
Phone: 011-33-76-88-39-03
FAX: 011-33-76-88-51-86

Dr. Noboru Watanabe
National Laboratory for
High Energy Physics
1-1 Oho-machi, Tsukuba-shi
Ibaraki-ken 305
JAPAN
Phone: 011-81-298-64-1171
Ext. 3601
FAX: 011-81-298-64-3202

Dr. Robert E. Williams
NIST
Building 235, A-106
Gaithersburg, MD 20899
Phone: 301-975-6876
FAX: 301-921-9847

Dr. Andre Vivaldi
Technicatome
Rue A. Ampere
B.P. 34
13762 Les Milles Cedex
FRANCE
Phone: 011-33-42-25-11-18
FAX: 011-33-42-25-18-62

Dr. Bernard W. Wehring
University of Texas at Austin
Nuclear Engineering Teaching Lab
10100 Burnet Road
Austin, TX 78758
Phone: 512-471-5787
FAX: 512-471-4589

Richard Woods
LANSCCE, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: 505-667-2939
FAX: 505-665-2676

INDEX

Speakers

Ageron, Paul 1, 291
Alexander, David 321
Bauer, Gunter S. 91, 255
Bernnat, Wolfgang 575
Breant, Paul 31, 439
Brewster, Peter M. 239
Carpenter, Jack M. 131, 529
Clark, David D. 559
Clausen, Kurt N. 57
Eberle, Cliff C. 299
Egelstaff, Peter A. 179
Fischer, Carl O. 81
Fischer, Walter E. 279, 449
Frazer, Wayne 379
Gobrecht, Klaus 19
Granada, J. R. 587
Hoffman, Helmut 395
Kawai, Takeshi 367, 593
Krähling, Ewald 543
Krull, Wilfried 65
Little, Robert C. 217
Lucas, Trevor 605
MacFarlane, Robert 193
McKibben, J. Charles 431
Morse, Fred A. v
Pynn, Roger 523
Russell, Gary J. i, 471, 565
Rowe, J. Michael 121
Sears, Varley F. 157
Sommer, Walter F. 343
Steichele, Erich 423
Utsuro, Masahiko 105

Watanabe, Noboru 491
West, Colin D. i, 409, 511
Yu, An. Sun. 557

Talks

A Design Concept for KENS-II Cold Neutron Source 491

A Practical Approach to the Polymerization of Liquid Methane in a Cold Moderator 605

An Alternative in the Heat Transfer Design: A Cold Neutron Source without Vacuum Insulation 291

Cold Moderators at Pulsed Spallation Sources: A Personal View 523

Cold Moderators for Pulsed Neutron Sources 131

Cold Moderator Scattering Kernels 193

Cold Neutron Source for the Present Munich Reactor 543

Cold Source Design for the New Munich Reactor 423

Cold Sources of the ORPHEE Reactor 31

Cross-Section Libraries and Kerma Factors 217

Evaluation and Validation of Neutron Cross-Sections for Liquid Hydrogen and Deuterium for the Design of Cold Neutron Sources 575

Existing Cold Sources at U.S. Reactors 121

Abstract i

Heating Rates in Reactor and Spallation Cold Sources 279

Historical Benchmarks and Experimental Problems 179

Hydrogen Safety 379

Introduction v

Instrumentation & Controls at Reactor Cold Neutron Sources (Including Links to Reactor Controls) 367

LANSCE Upgrade Cold Sources 471

Materials for Cold Neutron Sources: Cryogenic and Irradiation Effects 321

Monte Carlo Calculations for the CRNL Cold Neutron Source Design 239

Neutron Scattering and Transport Properties in Liquid H₂ and D₂ from a Synthetic Model 587

Neutron Slowing Down and Thermalization 157

Neutronic Design of the ILL Cold Sources: An Historical Perspective 1

New Cold Source for ORPHEE Reactor 439

Radiation Effects Concerns at a Spallation Source 343

Reactor Cold Sources in Japan 105

Some Concluding Remarks about Cold Moderator Development 529

Some Remarks on Design Criteria and Optimization Concerns for Cold Neutron Sources 255

Status of the University of Missouri-Columbia Research Reactor Upgrade 431

Summary - Reactor Cold Sources 511

The Advanced Neutron Source (ANS) 409

The Berlin Cold Neutron Source 81

The Cold Neutron Moderator for the Continuous Spallation Neutron Source SINQ 449

The Cold Neutron Multiplication of the Cold Neutron Source (CNS) at IAE, Beijing 557

The Cold Neutron Source at the FRJ-2 in Jülich 91

The Cornell University Cold Neutron Beam Facility Design Features 559

The GKSS Cold Neutron Source 65

The ILL Cold Sources 19

The LANSCE Target System 565

The Natural Convection Cooling with Vaporizing Deuterium for the Horizontally Arranged Cold Neutron Source of the HFR - Grenoble 395

The ORNL Liquid Nitrogen Simulation Facility 299

The RISO Cold Neutron Source 57

Thermodynamic Performance Tests of the Cold Neutron Source at the Reactor KUR 593