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WORKSHOP GROUP On MODERATOR PERFORMANCE ENHANCEMENT AND DEVELOPMENT ACTIVITIES (Progress and Needs)

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Summary

The workshop group broke into several subgroups for detailed discussions. However, in order to focus the efforts of the workshop group(s) and to develop topics for discussion, the group adopted the following charter:

Review the moderators in use at the present operating spallation neutron sources, and give an overview of improvements being made to enhance the neutronic performance of these moderators. Characterize the present thinking on "moderator types" for the next-generation, high-power (0.6-5 MW) pulsed spallation sources. Review ideas for improving the neutronic performance of moderators. Survey development activities underway and being contemplated for new moderator types, and facilities for measuring the neutronic performance of moderators. Look at activities aimed at providing new scattering kernels and improving existing ones. Discuss engineering issues that must be faced in practical moderator design.

Moderators Used in Existing Spallation Sources and Planned Improvements

At low-power (< 20 kW) pulsed spallation sources (KENS and IPNS), H_2O at ambient temperature, liquid CH_4 at 100 K, solid CH_4 at 20 K, and liquid H_2 at 20 K are used as moderators. For intermediate-power (100-200 kW) pulsed sources (Lujan Center and ISIS), solid CH_4 at 20 K is not a practical moderator material, and the moderators in use are H_2O at ambient temperature, liquid CH_4 at 100 K, and liquid H_2 at 20 K. At the quasi-continuous high-power (~1 MW) spallation source at PSI, D_2O at ambient temperature and liquid D_2 at 20 K are used as moderator materials. Planned moderator improvements at these existing sources include:

- partially coupled moderators (Lujan Center);
- upstream/back-scattering moderators (Lujan Center);
- reorientation of grooved moderator (IPNS); and
- conversion of liquid CH_4 at 100 K to solid CH_4 at 20 K (IPNS).

Conventional Moderator Performance Enhancement Techniques

There is a general trend toward increased intensity at the cost of resolution at spallation sources. Significant gains (e.g., up to ~70% for changing from B decoupler/liners to Cd decoupler/liners) can be realized by matching moderator time resolution to scientific instrument requirements.

Partially coupled moderators and poisoned reflectors can result in important gains (factors of 2 to 4) for instruments that can stand a broader neutron pulse width. The intensity from a liquid H_2 moderator at 20 K can be enhanced by the use of an optimized premoderator or cold Be reflector/filter. Matching the neutronic performance of a moderator to the instrument requirements is a key concept in all moderator designs.

Moderators for New High-Power Pulsed Spallation Sources (0.6-5 MW)

For high-power pulsed spallation sources, the first plans generally call for the same moderator materials (e.g., H_2O and liquid H_2) as for the intermediate-power spallation sources, with the same moderator performance enhancement techniques. Problems associated with either liquid or solid CH_4 are generally regarded as precluding their use in high-power spallation sources. However, the Japanese Hadron Facility (JHF) project is considering using a liquid CH_4 moderator at 0.6 MW spallation source due to the comparatively low-power operation and by placing the moderator in an upstream location with sufficient premoderation to reduce energy deposition (and damage) in the moderator. The Spallation Neutron Source (SNS) project may use a composite moderator of H_2O and liquid H_2 due to the small extrapolation of this approach from existing technology. The ESS project is considering using a flowing moderator of solid CH_4 pellets in liquid H_2. The SNS project may consider such a moderator for its second target station. The European Spallation Source (ESS) project is able to use present and future moderator developments because of the longer planning period for the ESS project. The Japanese Atomic Energy Research Institute (JAERI) is considering neutronically optimized liquid H_2 and H_2O moderators in their initial moderator suite for their 5-MW pulsed spallation source.

Advanced Cold Moderator Development

There is an international effort to develop Advanced Cold Moderators (ACoM). The goals of the ACoM effort are as follows:

- ✓ Develop a moderator that exceeds the neutronic performance of liquid H_2 by at least a factor of 2 for energies less than 5 meV.
- ✓ Advance a moderator with better slowing-down properties than liquid H_2.
- ✓ The moderator should be capable of operating in the temperature range 15-350 K.
- ✓ Have workable concept in 3-4 years.

Improved (and New) Scattering Kernels

The availability of well-validated scattering kernels for premoderator, moderator, reflector, and structural materials is a crucial aspect in the design and optimization stages of new target/moderator/reflector assemblies. In addition to the existing ENDFB-VI.2 data, the Synthetic Scattering Function (SSF) developed by Dr. Granada's group offers the possibility of generating scattering kernels for other potential cold moderator materials. The SSF has been recently integrated into the NJOY code, thus allowing for the preparation of cross sections in a standard format for neutronic calculations. New measurements at ANL have been made on the density-of-states of solid CH_4, which will lead to a new scattering kernel for this material. The LRMECS instrument at ANL is particularly useful in this regard, and continued measurements of this type on a variety of cold moderator materials would be extremely useful and are strongly encouraged. Work continues at LANL to prepare a quality-checked set of scattering kernels for distribution to the ICANS community and others by the end of 1998.

Experimental Facilities for Target/moderator/Reflector Neutronic Studies

The following table is a compilation (by Y. Kiyanagi) of experimental facilities where neutronic measurements of target/moderator/reflector configurations are possible. The table summarizes the characteristics of these facilities.

Table I. Experimental Facilities Worldwide

Facility	Particle Type Energy	Current Rep Rate Pulse Width	Comments
Hokkaido Linac (Japan)	electrons < 0.045 GeV	< 20 μA < 100 pps 0.01-3 μs	Two cold sources (permanent and portable); beam size and distribution of produced neutrons are adjustable; TOF
AGS (USA)	protons 1.5-24 GeV	10 μA @ 24 GeV 1 μA @ 2.4 GeV 0.5 pps 0.04-2 μs	Power deposition study (target, moderator, reflector); physics parameters (spatial and temporal); TOF
JESSICA (Germany)	protons 0.1-2.5 GeV	1.6×10^{-6} μA 0.1 pps 1 μs	Cold source test facility; power deposition measurements; geometric optimization; easy test of various moderator and reflector materials; TOF
KENS Beam Dump (Japan)	Protons 0.5 GeV	6 μA maximum 20 pps ~0.05 μs	Need to drill the shield door to have a neutron flight path; safety assessments will be required before use; TOF
Bariloche Linac (Argentina)	Electrons <0.03 GeV	< 2.5 μA < 100 pps 1.4 μs	Lead target; ambient or liquid-nitrogen cooled moderator; total cross section measurements; TOF

Moderator Engineering Issues

Curved moderator viewed surfaces are preferable from a structural viewpoint when constructing moderator canisters. Moderator field-of-view and "effective thickness" are important design considerations. Safety criteria for spallation cold sources generally employ triple containment. Bellows at cryogenic temperatures are not only useful, but in many cases are essential in the design of a cold moderator cooling circuit. Cold source cooling system design should employ good sound engineering practices.

General Issues

Cooling of neutron decouplers at high-power pulsed spallation neutron sources deserves further attention, as well as the materials (and perhaps development of materials) for this application. It is important to keep in mind the need to be able to measure the ortho/para-hydrogen concentration in an operating liquid H_2 moderator at a pulsed spallation source. The communication channels(s) between moderator designers and scientific instrument designers needs to be kept up (and improved). It is vital to get moderator performance criteria from the instrument designers as soon as possible in a spallation source project so that the proper moderators can be designed to meet their needs.

More Detailed Discussion

Below are some more detailed thoughts expressed by some of the sub-groups. We have made no attempt to alter their comments in any substantive way. We have acknowledged the contributors as they were given to us (the leader of the sub-group is listed first).

Conventional Moderator Performance Enhancement Techniques
(P. Ferguson, J. Carpenter, E. Iverson, M. Teshigawara, and N. Watanabe)

There is a general trend toward increased neutron intensity at the cost of resolution at the existing spallation sources. For example,

- ✓ ZING-P, E_d >100 eV
- ✓ KENS, E_d 97 eV for H_2O moderator
- ✓ ISIS, E_d 1-3 eV
- ✓ IPNS, E_d ~0.3-0.5 eV
- ✓ Lujan Center, E_d ~0.3-0.5 eV,

where, E_d is the decoupling energy of the decoupler material, which is generally Cd or B.

For the Lujan Center, a 70% intensity gain (E< 100 eV) is seen when changing E_d from ~ 3 eV to 0.5 eV (i.e., from B to Cd). Additional gains may be obtained in changing from Cd to Gd decoupling by using an AlGd alloy with which IPNS has some experience. Matching moderator time-resolution to the instrument requirements is very important and intensity is lost when the pulse resolution is much better than that which the instrument requires.

Neutronic gains up to a factor of 6-7 can be obtained when moving from a fully decoupled system to a fully coupled system at the expense of neutron pulse width. Gains in intensity up to a factor of ~4 can be seen in a poisoned reflector system being installed at the Lujan Center. There is a significant amount of work that can be done to gain intensity at existing spallation sources by matching the neutron pulse width to the scientific instrument requirements.

Present moderator studies at JAERI indicate substantial neutronic gains on the order of 30-40% for optimized extended premoderator designs. In addition, cold Be reflector/filter calculations at Los Alamos show possible gains of 50-50% in long wavelength neutrons without much increase in the neutron pulse width.

IPNS is planning to move from a horizontal-grooved to a vertical-grooved moderator. The net moderator performance will probably be the same; however, the performance of the vertical reflectometers which view the moderator may increase substantially (~70%). This further highlights the importance of moderator/instrument matching.

Finally, a ring moderator concept was presented which shows some promise and deserves further study.

Moderators for New High-Power Pulsed Spallation Sources (0.6-5 MW)
(L. Charlton, D. Picton, and M. Teshigawara)

The first plans for moderators at high-power sources generally call for the same moderator materials (liquid H_2O, liquid D_2O, liquid H_2, and liquid D_2) as moderators at low-power sources, with the same moderator performance-enhancement techniques as used for the lower-powered spallation target systems. The SNS project may use a composite moderator due to the small extrapolation from existing technology. (Note: the new Los Alamos spallation target system recently installed and ready for commissioning in the summer of 1998 employs both a composite Be/H_2O moderator and Be/liquid H_2 moderator in their upstream/back-scattering moderator positions).

Radiation damage problems associated with liquid and solid CH_4 moderators are generally regarded as precluding their use in the same manner as they are used in low-power spallation sources. The ESS program is considering using a pelletized CH_4 moderator and the SNS may consider such a moderator for a second target station. The JHF program is considering using a liquid CH_4 moderator due to the comparatively low-power (0.6 MW) of the source by combining upstream placement of the moderator with premoderators to reduce energy deposition and radiation damage in the CH_4 moderator.

The ESS program is able to use both present and more advanced moderator concepts in their planning due to the longer timetable being considered for the effort.

New High-Power Pulsed Sources (0.6-5 MW)

There are several projects/programs under consideration that extend the power of spallation source significantly. These new sources are summarized below.

JHF – The JHF project initially calls for a Neutron Arena with a pulsed spallation source operating at 0.6 MW (200 μA of 3-GeV protons at 25 Hz), with possible operation at 50 Hz and 1.2 MW.

SNS - The SNS project will have two liquid H_2 moderators on the top of the target system, and two liquid H_2O moderators on the bottom. The two ambient-temperature liquid H_2O moderators will produce neutrons with an energy spectrum with a peak at ~30 meV. Both of the liquid H_2O moderators will be decoupled and poisoned, with the neutron decoupling done by surrounding all sides of the moderator (except for the viewed surface) with 1-mm of Cd. The poisoning will be done by using 50 μm of Gd placed parallel to the viewed surfaces of the moderator. The exact depth of the poison layer will be determined later by instrument requirements.

The upstream liquid H_2 moderator will be decoupled and poisoned in the same manner as the upstream liquid H_2O moderator. The downstream liquid H_2 moderator will be fully coupled to maximize the neutron output. This selection of moderators was made to be as consistent as possible with the 10 instruments chosen as an initial set.

Preliminary optimization of the moderators (as well as some of the other SNS target station components) was done using a "figure-of-merit" given by the moderator intensity divided by the square of the neutron pulse width. This was done only for the initial stages of the design. Later optimization will be done using a full interaction with the instrument designers and with the input provided by their state-of-the-art computer codes used in instrument design. It was felt that a simple figure-of-merit provided a valuable tool for early studies, particularly when the set of instruments is not finally determined and when time constraints preclude a lengthy consideration of the requirements of the 10 initial instruments.

ESS - The ESS reference design incorporates two target stations: a) the "H" station (high-repetition rate) which will probably operate at ~50 Hz, taking 4 out of 5 pulses, and the "L" station (low-repetition rate), which will probably operate at ~10 Hz, taking 1 out of 5 pulses.

The "H" station will be similar to the present ISIS configuration and will probably incorporate two 300 K H_2O moderators and two 20 K liquid H_2 moderators. The "L" station will be used exclusively for cold neutron production, and will incorporate two or more liquid H_2 moderators.

The main issues for further moderator studies are associated with the cold moderators. On the "H" station, at least one of the liquid H_2 moderators will take the place of a 100 K liquid CH_4 moderator in the expectation that the lifetime of a liquid CH_4 would be too short on the ESS due to radiation damage problems. A study will need to be carried out to identify an optimum moderator configuration, e.g., a 20 K liquid H_2 moderator with a 300 K H_2O premoderator. Other concepts, e.g., a pelletized solid CH_4 moderator in liquid H_2 should also be considered.

In the case of the "L" station, it is likely that at least one of the moderators will be wholly or partially coupled with the reflector to optimize neutron intensity as opposed to pulse width. A detailed study will be required in order to fully optimize the target-moderator-reflector configuration. A similar study is envisaged for the proposed second target station for ISIS.

JAERI – The JAERI Neutron Science Project has a vision to be the "neutron supplier" for Japan into the next century. The present thinking is to provide a 5 MW pulsed spallation source supplying cold, thermal, and epithermal neutrons. At present, the target is assumed to be a liquid metal target (presumably mercury), employing horizontal proton beam insertion. Since about one third of the total available angles around the JAERI spallation source is allocated to each field of experiments utilizing cold, thermal, or epithermal neutrons, the required angular coverage for each kind of moderator(s) becomes about 100 degrees. This angular coverage cannot be covered by one viewed surface, and two viewed surfaces become indispensable. For a moderator having only one viewed surface, two such moderators are required.

For a cold neutron source, a coupled moderator composed of liquid H_2 or supercritical H_2 plus a hydrogenous premoderator (e.g., H_2O at ambient temperature). This particular moderator configuration is sometimes called a coupled liquid H_2 moderator with a premoderator. This moderator has been developed to provide higher time-integrated and peak cold neutron intensities than a conventional decoupled liquid H_2 moderator or solid CH_4 moderator does. This moderator can satisfy high-intensity experiments such as SANS, reflectrometry, etc. in which the time-integrated intensity is important, together with high-resolution experiments in which the peak intensity is essential. Two such moderators are envisioned since this moderator has only one viewed surface.

For high-resolution thermal neutron experiments, a decoupled liquid H_2 moderator with a interleaved poison sheet is being considered, since a decoupled solid or liquid CH_4 moderator probably cannot as yet be effectively used at MW-level spallation sources. R&D of a mixed moderator for this purpose will require a long period. Optimization studies on a decoupled

/poisoned liquid H_2 moderator is under progress. At the present stage of the design work, a high-intensity thermal neutron moderator is not being considered since high-resolution thermal neutron experiments are much more promising than high-intensity ones at an SPSS.

For a high-resolution epithermal neutron moderator, a H_2O moderator of an appropriate thickness (tentatively ~3 cm) is being considered. The optimal thickness will be determined after extensive discussions by users on the most interesting energy range in future science.

Advanced Cold Moderator Development
(G. Bauer, E. Iverson, and E. Shabalin)

The term advanced cold moderators is meant to apply to such systems which have a potential to enhance the performance of cold moderators over what is currently achievable on any particular type of source but cannot be realized without developed technologies.

Two recent studies for next generation neutron sources (ESS, Europe, and the SNS, USA) clearly establish the overwhelming need for cryogenic moderators: 36 out of 45 instruments proposed for the ESS; and 33 out of 37 for the SNS requested cryogenic moderators to supply them with neutrons. Currently the only cryogenic moderator systems that can be operated reliably on a high-flux neutron source are based on liquid hydrogen. Development is desirable in two ways:

- ➢ It was shown by calculations as well as by experience on low-power spallation sources that a factor of three or more could be gained in useful intensity, if a neutronically optimal moderator substance could be used.

- ➢ For every neutron energy, there exists a moderator temperature at which the intensity output is maximum. Therefore, a system that could be operated in a wide temperature range would provide unparalleled flexibility to adjust to evolving needs.

If realized, this would be a more efficient way of improving source performance than any potential increase in source power.

According to current thinking, the system would be based on heterogeneously cooled pellets of methane or a clathrate (e.g., methane clathrate) that would be thermally annealed at appropriate intervals to release stored energy. Pellets would also be replaced continuously or batchwise at a rate required by the accumulation of non-annealable radiation damage, which would degrade performance. Data on the excitation frequency spectrum of methane clathrate have recently become available, which clearly show the presence of intense low energy peaks at 1 meV and higher as well as the full frequency spectrum of water. The hope that methane clathrate might make a good moderator is largely based on this finding.

In order to ultimately realize such a system, a large body of work has to be carried out:

- ✓ Other promising candidate moderator materials should be identified and their suitability for the present purpose should be examined, based on their physical and chemical properties. Where such information is not available in the literature, suitable experiments must be carried out.
- ✓ Quantitative information on the neutronic properties (cross sections, density of states) must be collected or provided through suitable experiments.

- ✓ Scattering kernels that allow one to predict the performance as a moderator and its optimization by computational methods must be evaluated.
- ✓ Radiation effects must be studied to predict the allowable residence time in the high radiation field near the primary neutron source.
- ✓ Methods of fabrication of the moderator material in a suitable form and of cooling must be developed.
- ✓ In the case of solids, the problem of transportation to and from the moderator vessel must be solved.
- ✓ Ways to anneal radiation damage and to recycle the material, respectively to identify and sort out irreparably damaged parts must be developed.
- ✓ Prototypic setups must be constructed to test the practicality and reliability of the concepts developed.
- ✓ Full load tests must be carried out to make sure that no rate dependent effects exist which falsify the results obtained at low loads.

In an attempt to accomplish these tasks, an international collaboration is in formation, for which 12 laboratories have expressed interest so far. A working plan has been established with the following milestones:

- ➢ 01/1999 - Room temperature pellet transport: working model
- ➢ 06/1999 - Moderator materials: neutronic performance examined
- ➢ 03/2000 - Moderator materials: radiation effects; pellet production methods developed
- ➢ 01/2003 - Integrated Test Assembly ready

Five papers on the subject in question have been presented at the ICANS-XIV meeting.

Moderator Engineering Issues
(T. Lucas, M. Furusaka, H. Jeyck, Y. Ichoro, K. Clauson, H. Barnert-Weimer, and T. Scott)

As with any equipment, the design of a cold source system relies on a solidly based and constructively thought out specification that should be supportable and should represent an optimization of the true physics requirements and engineering feasibility. This subgroup discussed some typical topics as outlined below.

How Important Are Flat Moderator Viewing Surfaces? - Clauson (RISO) took the view that reliability is the key factor and that the added thickness required by flat surfaces at internal pressures up to 15 bar abs would largely negate the advantage. Furthermore, no problems of asymmetry had been observed from their curved moderator vessels. This is a problem that frequently arises in practical moderator design.

Moderator Viewing Surface Size and Thickness - As a general rule, the moderator should be close to the sizes of the beam viewing area. However, Furusaka indicated that an optimization method exists that can be applied as a general rule. The optimum thickness of a moderator should be applied to the meridian plane, as this is most representative of neutron thickness.

Accepted Safety Criteria for Cold Sources - The generally accepted requirements for a cold source system, with particular reference to those installed in a reactor, is the provision of a secondary inert barrier around cold source components. This includes vacuum insulated components (representing triple containment).

Use of Bellows at Cryogenic Temperatures - Bellows can suffer from having their own problems especially at cryogenic temperatures. However, it was generally agreed that used intelligently, they are not only useful, but, in many cases, essential. Clausson reported that bellows used in their cold moderator system have given no problems throughout the life of the system.

General Engineering Practices - The wisdom of allowing manufacturers of specialist equipment an opportunity to comment on a design was expressed. This can result in the best possible compromise between physics, engineering, and manufacturing limitations.

Liquid Methane as a Moderator - Polymerization of liquid CH_4 is a well-known phenomenon in a radiation field. However, the resulting gains over liquid H_2 has prompted Furusaka to reconsider its possible use up to 1 MW. Experience with the ISIS system indicates that at a power level of 0.2 MW, the methane inventory requires to changing every one to two days, and the moderator vessel blocks up in about half an operational year. However, Lucas believes that a major part of the problem is an inability to adequately remove hydrogen gas produced as a by-product during irradiation. Also, better flow through the moderator would lower the transport time through the moderator and help reduce buildup of solid materials in the vessel. Provided a cryogenic vessel assembly could be made easier to replace (in say 3-4 days), an annual replacement program would probably be acceptable. With design improvements, this just might make liquid CH_4 a more practical moderator for higher-power spallation sources.

Poison Layers in Moderator Vessels - The warning was voiced that poison layers in a moderator can represent a significant heat load that can easily be neglected. It is essential that this be calculated as a heat generator, and be factored in with the other heat loads.

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