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Cold Neutron Sources: Practical Considerations and Modern Research

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COLD NEUTRON SOURCES: PRACTICAL CONSIDERATIONS AND MODERN RESEARCH

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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

Free neutrons are liberated by a variety of nuclear reactions. However, they are released at energies far above those that are typically of use for studying the structure and dynamics of materials. For such studies, thermal and cold neutrons are usually required. Both need a moderator, but a strong cold neutron flux requires a specialized, hydrogen-rich, cryogenic moderator, such as liquid hydrogen or liquid deuterium and solid or liquid methane. Cold neutrons — conventionally those with energies below 5 meV and wavelengths longer than ca. 4 Å (0.4 nm) — are particularly useful for studying materials characterized by large dimensions (e.g. polymers, biological molecules) and low-energy vibrational states, as well as certain imaging applications.

Since the first cold neutron source was installed in the BEPO research reactor in Harwell, United Kingdom, in 1956, a number of systems have been developed at research reactors and accelerator based neutron sources around the world, and considerable knowledge has been gained. This publication outlines many of the considerations for building a cold neutron source, including neutronics and heat removal, design considerations, materials choices and fabrication methods, safety, and licensing. It also describes some typical project management considerations and the path from installation, commissioning and benchmarking to operation and eventual decommissioning. It ends with a section describing recent research and development themes including modern moderator materials, catalysts for parahydrogen, geometrical optimization, scattering kernels and recent developments in Monte Carlo codes for modelling and optimization.

This publication stems from a technical meeting held in October 2018 with participants from 15 Member States, and a coordinated research project that ran from 2014 to 2019 involving 14 institutions.

The IAEA officers responsible for this publication were I. Swainson and N. Pessoa Barradas of the Division of Physical and Chemical Sciences.

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1. INTRODUCTION

1.1. BACKGROUND

The nucleus is made up of two basic particles (nucleons): protons and neutrons. The ratio of protons to neutrons strongly affects the stability of a nucleus via the binding energy, and the stable nuclei are found in the famous 'line of stability'. Neutrons as free particles are not stable, but beta decay with a mean lifetime of ca. 880 s [1–2] ($T_{½}$ of ca. 610 s), although there is some disagreement on the precise value of this value depending on the measurement technique used [2–3].

The energy (E), wavelength (λ), and velocity (v) of a neutron are related by the familiar equations:

$$E = \frac{1}{2}mv^2 = h\upsilon = \frac{h^2}{2m\lambda^2} \quad (1)$$

where m is the mass of the neutron, and h is the Planck constant.

Neutrons are neutral, spin-half particles. Their neutrality means they can penetrate deeply into most materials, as their interaction is with the nuclei via the strong nuclear force and not with the electron cloud [4–5]. The unpaired spin of the neutron gives rise to a second interaction, this time with unpaired electrons in the outer orbitals, making neutrons a valuable tool for studying magnetic materials [4–6]. Table 1 gives a set of definitions of neutron energy groups encountered in the literature for neutron scattering and neutron physics. The energies of interest to practitioners of neutron scattering and imaging typically lie from the epithermal to the cold range. Very cold and ultracold neutrons are for studies of fundamental properties of neutrons and their interactions [7–9]. Definitions are not consistent between different institutions and research groups, so care is needed when using such labels; e.g., 'epithermal' may be defined as up to 0.1 keV, up to 1 keV [5], or up to 10 keV [10]. The term 'fast' can also be used for neutrons above 1 keV [5].

TABLE 1. COMMON DEFINITIONS OF NEUTRON ENERGY GROUPS

Neutron group	Energy	Wavelength, Å
Fast	> 10 keV	≲ 0.03
Epithermal	0.5 eV–10 keV	0.4–0.03
Hot	0.1 eV–1 eV	0.3–0.9
Thermal	< 0.5 eV	≳ 0.4
Cold	< 5 meV	≳ 4
Very cold	0.3 μeV–0.1 meV	28–50
Ultracold	≲ 0.3 μeV	≳ 500

Note: The boundary in energy between ultracold and very cold is often taken as the height of the positive neutron optical potential, for which ^{58}Ni has the greatest value (~ 340 neV). The upper bound in energy for cold neutrons is usually taken as the cut-off energy for a Be filter (~ 5 meV).

The neutron flux at the earth's surface is weak and comes from cosmic ray interactions and from terrestrial sources, including spontaneous fission and (α, n) reactions. The natural thermal flux is of the order of 10^{-3} cm$^{-2}\cdot$s^{-1} [11]. Due to the continuous decay of free neutrons, neutrons have to be continuously produced via nuclear reactions for experimental purposes. Suitable reactions include (α, n) reactions produced from a strong α emitter in close proximity to a weakly bound light nucleus: PuBe, AmBe, AmLi. Spontaneous neutron emission as a result of spontaneous fission from some nuclei occurs, such as ^{252}Cf. Isotopic sources are, however, quite weak and are not generally used for neutron scattering techniques but can be used for detector and electronics development and calibration; e.g., the neutron tagging facility at Lund

University, Sweden [12]. Small neutron generators (D–D or D–T sources) are low flux sources of neutrons chiefly used for analytical purposes [13].

The most common sources used for neutron scattering purposes are:

- Fission reactors. Both light- and heavy-water research reactors are used for neutron scattering purposes.[1] Almost all are steady state sources, although pulsed reactors exist, such as IBR-2 at the Joint Institutes for Nuclear Research, Dubna, Russian Federation. The beam from a steady state reactor can also be 'chopped' into pulses for a particular beamline;
- Accelerator systems. There are many different accelerator technologies that can produce neutrons. The most powerful, highest flux sources are based on the spallation process. However, there are few of these in the world due to their expense and technical demands. A variety of lower energy accelerator systems exist that can produce neutrons for neutron scattering, which are collectively called Compact Accelerator based Neutron Sources (CANS), described in a recent IAEA publication [14]. Accelerator systems can be either steady state (e.g., the SINQ spallation source, Switzerland [15]) or pulsed. Most accelerator systems dedicated to neutron scattering are pulsed and the instruments based on the time-of-flight method [16].

For most neutron scattering and imaging techniques, neutrons with energies from the lower epithermal, thermal, or cold range are required. The first thermal moderators were those required to maintain the fission reaction: D_2O or H_2O. Indeed, neutron scattering was pioneered with thermal beams at some of the very first high-flux reactor sources, such as NRX and NRU in Canada, and HFIR in the USA, and for which a joint Nobel Prize was awarded in 1994 for the development of neutron diffraction (elastic[2] neutron scattering) and the triple-axis spectrometer for inelastic neutron scattering.

Aa a common feature of reactor and accelerator production of neutrons is that a large portion of the primary energies of the neutrons are either in the 'fast' or upper 'intermediate' energies (Figure 1), many orders of magnitude above the thermal energy of a moderator. Therefore, the probability is extremely high that with each early collision, kinetic energy is transferred from the neutron to the moderator via an elastic[2] collision ('down scattering'). The properties of a good moderator are described in Section 4 of Ref. [14] and in more detail in Ref. [5].

The average kinetic energy of the moderating nuclei is set by the ambient temperature. A corresponding neutron temperature can also be assigned, based on Maxwell–Boltzmann statistics. Rather than using the mean speed of an ensemble of neutrons at a given temperature, T, the modal speed, v_{mod}, is used, which is related to the neutron temperature by:

$$v_{\mathrm{mod}}=\sqrt{\frac{2k_{\mathrm{B}}T}{m}} \tag{2}$$

The term 'thermal neutrons' covers a range of energies (Table 1) and strictly speaking refers to neutrons in equilibrium with a moderator at 293 K (i.e., neutrons with the Maxwellian distribution corresponding to room temperature). However, it is often common to speak of 'a

[1] IAEA Research Reactor database, https://nucleus.iaea.org/rrdb/#/home.

[2] A note on the terms 'elastic' and 'inelastic', which have different meanings in the moderator and neutron scattering fields. In theory, a fast neutron can transfer all its kinetic energy to a proton in a single collision in a moderator, via an 'elastic collision', so-called as all kinetic energy is transferred as kinetic energy to the proton. However, in the field of neutron scattering, 'elastic' scattering is scattering without any change in a neutron's incoming and outgoing energies (e.g., diffraction), whereas scattering that transfers energy from a neutron to a material is termed 'inelastic' scattering. This needs to be borne in mind when reading both literatures.

thermal neutron' in which case the single energy referred to is usually 25.4 meV (1.8 Å), which corresponds to the peak of the Maxwellian for a moderator temperature of $T = 293$ K [5].

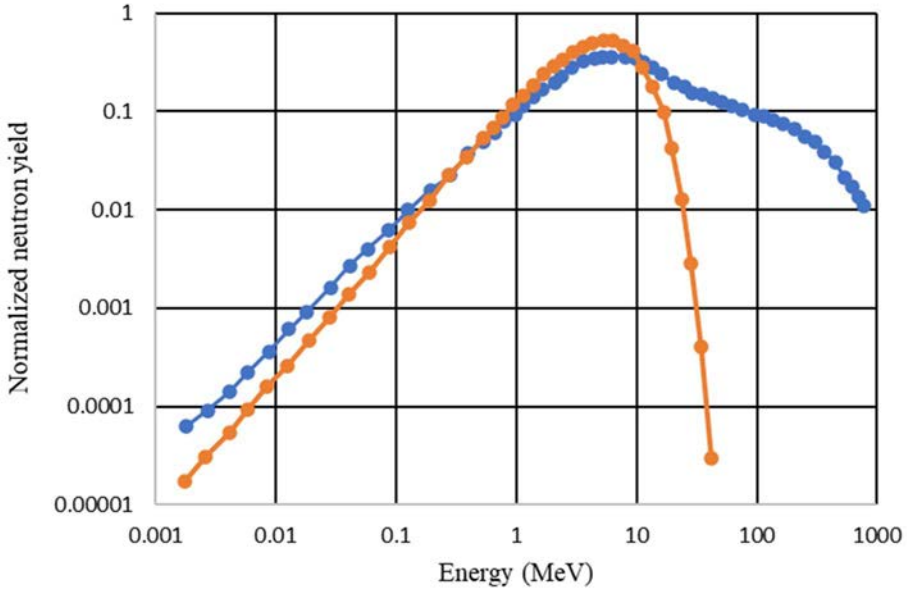

FIG. 1. Neutron spectrum from a W spallation target (blue) and from fission (orange). Data taken from Ref. [17]

The main application of cold neutrons is to study materials via neutron scattering and imaging techniques. Over the past fifty years there has been considerable interest in cold neutrons – these are neutrons with energies below 5 meV (Figure 2). The somewhat arbitrary definition of cold neutrons is due to the fact that Be (natural abundance, 100% ^{9}Be) is usually used as a neutron beam filter. For neutrons with $\lambda < 4$ Å ($E > 5$ meV) the scattering cross section of ^{9}Be is ~6 b. For longer wavelengths (lower energies) where Bragg scattering is impossible, the cross section becomes more strongly temperature-dependent and decreases rapidly to ~0.5 b at room temperature and to ~0.05 b if cooled below 100 K.

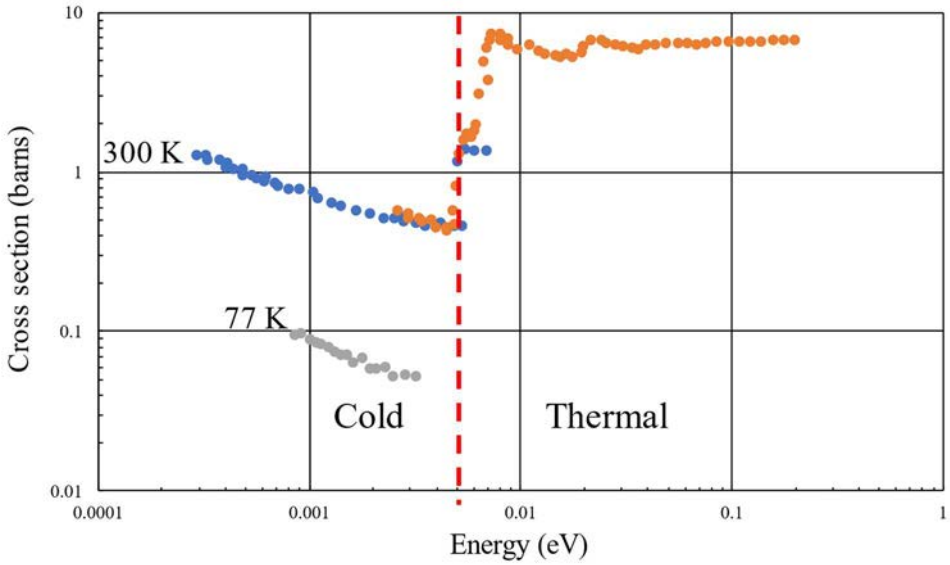

FIG. 2. Microscopic scattering cross section of ^{9}Be powder as a function of energy from two data sets at 300 K (blue and orange) with one set from 77 K (grey) together with the 5 meV boundary (dotted red line) for the conventional upper bound of 'cold neutrons'. Data at 300 K from Ref. [18] and at 77 K from Ref. [19].

The de Broglie wavelength of a neutron $\lambda(\text{cm}) = \frac{h}{\sqrt{m_n T_n}} = \frac{4.5 \times 10^{-10}}{\sqrt{T_{n\,(eV)}}}$ becomes comparable to the size of an atom (~10^{-8} cm) already at a neutron energy $T_n \approx 0.02$ eV (~237 K). Cold neutrons with their longer wavelengths are well suited for elastic neutron scattering from objects with large characteristic dimensions, and also to study the 'soft' excitations that are characteristic of slow molecular reorientation etc. Besides, inelastic cold neutron scattering can be used to study such effects as phonon dispersion laws in crystals, thermal diffusion of atoms in liquids and gases, density changes at phase transitions, and the interrelations between magnetic moments in magnetic materials. To produce cold neutrons, different (cryogenic) moderator systems are required, which is the subject of this publication. Common applications of neutrons for neutron scattering and imaging have been described in three IAEA publications [14, 20–21]. Further description of neutron beam techniques and moderation, including the materials used for cold moderators, are available in several books [4–5].

The efficiency of a source as a generator of neutrons largely depends on the properties of the material used as the moderating medium. The neutron moderation process is determined by the values related to the elementary act of collision of the neutron with the nucleus of the moderator material. For neutrons with energies substantially above thermal, the collision is considered in the framework of classical mechanics as an elastic collision of two balls: the scattering nucleus and the neutron. The probability of such an interaction is related to the macroscopic scattering cross section (Σ_s) of the moderating material. Apart from unwanted neutron leakage from the moderator, internal losses due to absorption, related to the macroscopic absorption cross section (Σ_a), need to be minimized. The mean path lengths between scattering (l_s) or absorption (l_a) process are inversely related to their respective cross sections.

The average loss of energy in a single collision is characterized by the parameter:

$$\xi = \ln\frac{\overline{E_0}}{E} = 1 + \frac{(A-1)^2}{2A}\ln\left(\frac{A-1}{A+1}\right) \tag{3}$$

Where $\bar{E}_0$ and E are the energies of the neutron before and after the collision, respectively, and A is the atomic weight of the nucleus of the moderator material. It can be concluded from the above relations that the ideal moderator material would have the smallest possible atomic weight (large ξ) and neutron absorption cross section (Σ_a) and the largest possible neutron scattering cross section (Σ_s). The value $\frac{\xi}{l_s}$, which gives the average loss of neutron energy per unit length, l_s, in the moderator, is commonly referred to as the 'moderating efficiency' of the material. At lower neutron energies, the cross sections cease being dominated solely by the nuclei of the moderator material and become sensitive to material structure (neutron diffraction, small angle scattering, etc) and dynamics (inelastic neutron scattering). In particular, for efficient cold moderators, the 'density of states' of low-energy excitations becomes important to determine cold moderator efficiency. Once a neutron's energy approaches being that of the average kinetic energy of the moderating nuclei it is said to become 'thermalized' and the likelihood of 'down scattering' and 'up scattering' (gain of energy by the neutron from the moderator) become similar.

For accelerators, the neutron producing target, moderator, and reflector geometry can be optimised. Another factor becomes of concern for short pulsed accelerator sources*:* the slowing down time of the neutrons in the system can smear out the initial pulse duration set by the proton beam pulse on the target and degrade the time-resolution of the neutron beam instruments. This is described in Section 4.1 and other references [5, 16, 22].

The lowest energy fractions of neutrons are known as very cold and ultracold neutrons. Very cold neutrons exhibit the property to 'see' not just separate groups of atoms but their aggregates in the form of conglomerates or density fluctuations in matter, because the wavelength of very cold neutrons becomes commensurate with the sizes of such fluctuations [23]. The slowest neutrons are traditionally referred to as ultracold neutrons [7]. The wavelengths corresponding to these energies exceed the critical wavelength for total reflection for the majority of substances, so that ultracold neutrons experience mirror reflection at any angle of incidence from the surfaces of a medium with a positive coherent scattering amplitude. They can, therefore, be stored inside a closed volume and transported through appropriate neutron guides to experimental stations. Ultracold neutrons are used for fundamental physics studies, e.g., the search for a neutron electric dipole moment, search for neutron–antineutron oscillations, measuring the free neutron mean lifetime etc., see for example Ref. [24].

1.2. OBJECTIVE

The objective of this publication is to provide practical experience of the design and operation of cold neutron sources (CNSs) at research reactors and at accelerator based neutron sources and an overview of some modern developments in cold moderators.

1.3. SCOPE

The publication covers practical considerations around various designs of CNSs at reactors and accelerators. It also gives an overview of the research activities of the Coordinated Research Project F12026 entitled 'Advanced Cold Moderators for Intense Cold Neutron Beams in Materials Research', which ran from 2014 to 2019.[3] While very cold and ultracold neutron sources are mentioned, detailed descriptions of such facilities are out of scope of this publication.

1.4. STRUCTURE

Section 2 provides a description of a CNS, an overview of many historical cold sources, and the performance gains that can be expected from a CNS. Section 3 discusses feasibility studies for such systems and the typical considerations around undertaking such a project. Section 4 discusses design of such systems including the topics of neutronics, materials selection and properties, optimization of performance, heat load, thermohydraulics, and the uncertainties to be considered. Section 5 gives a high level overview of some of the major considerations in manufacturing, including quality, machining, welding, sampling, and testing. Section 6 discusses some of the major safety considerations when it comes to licensing such a facility. Section 7 discusses installation and operation of a CNS, as well as the characterization and benchmarking of its performance once installed. Section 8 gives an overview of some of the particular considerations surrounding project management for such a facility, including quality, interfacing issues, prototyping, manufacturing, and acceptance testing. Section 9 discusses operation and reliability and Section 10 concerns the lifetime of such sources, waste, and decommissioning activities. The final section gives a high-level overview of some of the active topics of research in cold moderators, mostly built around the research activities undertaken for CRP F12026.

Three Appendices provide information on quality assurance for CNS manufacturing, on quality assurance inspection plan, and on tritium activity in deuterium based CNSs. Annexes I and II describe experiences at university research reactors in the USA, Annex III that at the ISIS

[3] https://www.iaea.org/projects/crp/f12026.

spallation source in the UK, and Annex IV that at the larger HANARO reactor in the Republic of Korea. Annex V provides the answers given by respondents to a questionnaire on the lifetime, radioactive waste, and decommissioning of CNSs.

2. HISTORY AND OVERVIEW OF COLD NEUTRON SOURCES

Recent IAEA publications have covered the topics of compact accelerator based neutrons sources [14] and neutron scattering with low and medium flux neutron sources [20]. This publication focuses on CNSs at such research reactor and accelerator based neutron sources. Cold neutron sources at major neutron sources are characterized by high neutron fluxes and significant volumes which, coupled with neutron guides, accommodate a wide range of user experiments on a large number of neutron scattering instruments, occupying significant floorspace. Those advantages come at a cost. Such CNSs demand significant financial and technical resources to design, manufacture, install, operate, maintain, and decommission. In particular, compliance with nuclear safety regulations when applicable can be highly demanding for the owner/operator.

2.1. HISTORY OF DEVELOPMENT

Conventionally, reactors and accelerators are called 'primary' neutron sources, and sources of cold neutrons and hot neutrons – 'secondary' neutron sources. An overview of considerations for in-pile cold and hot sources for research reactors is given in Ref. [25]. The idea of producing cold neutrons using paraffin wax cooled with liquid air, liquid methane, or liquid hydrogen as moderators was first explored at cyclotrons [26–27].

The first attempt to use a cooled moderator inside a research reactor was at Harwell, UK in 1956 [28], where, after studying various hydrogen-containing moderators outside the reactor, a liquid hydrogen moderator was installed in the BEPO reactor. In Table 2, an historical list of many of the reactor based CNSs is presented in chronological order of their creation. Many of these sources installed at first-generation research reactors have been decommissioned due to the shutdown of research reactors that have reached the end of their useful life.

At the present time, there are 222 research reactors in operation in 52 countries.[1] The key objective of a CNS at research reactors is to perform neutron research. The majority of reactors in operation today have been so for several decades, and their number is decreasing through time, whereas the demand for neutron beams is expected to increase. These two facts may be satisfied by the construction of more, lower-cost CANS and by modernizing existing reactors. Currently, about one in fifteen operational research reactors are equipped with one or more CNSs, and in such cases, usually more than 60% of the suite of experimental installations of a reactor utilize cold neutron beams.

Over the past five decades, about sixty different CNSs were created at reactors and accelerators around the world. Most CNSs were and are being created at steady-state reactors. The 1960s and 70s saw the creation of second-generation reactors, which were intended for both radiation research and research with cold neutron beams. The 1980s saw the greatest number of CNSs created, due to the creation of third-generation reactors and the use of accelerators for neutron beam research. By this time, sufficient experience in the creation of CNSs had been gained, which allowed the modernization of outdated installations. At the same time, the active creation of more advanced CNSs during this period was directly related to the development of neutron beam centres in the USA and in the Asia–Pacific region (Japan, China, Republic of Korea, Australia). In the history of CNSs, the largest number of sources was created in Europe – about 69% of total quantity, in the USA – 16% and in the Asia–Pacific region – 15%. An IAEA database containing neutron beam instruments and CNSs is available online.[4] A directory of

[4] https://nucleus.iaea.org/sites/accelerators/Pages/Interactive-Map-of-NB-Instruments.aspx.

CNSs, produced by Klaus Gobrecht, was last updated in 2007.[5] At the present time, about ten CNSs are at the design or assembly stage.

During the 1980s, the advancement of accelerator technology created the situation where the performances of spallation neutron sources became similar to the nuclear reactors. The first pulsed spallation sources were ZING-P and ZING-P' (Argonne, USA) in the mid-1970s, KENS (KEK, Japan) in 1980, and IPNS (Argonne, USA) in 1981, where proton beam energies were ~500 MeV, with proton beam powers up to 3–7 kW. Then, in the mid-1980s, the ISIS Neutron and Muon Source started operating with a beam energy of 800 MeV, beam power ~160 kW, beam pulse length of 1 μs, and repetition rate of 50 Hz. This facility, which is now the ISIS Target Station 1 (TS-1), initially had two CNSs (liquid hydrogen at 20 K and liquid methane at 110 K) but in 2008, when ISIS Target Station 2 (TS-2) started operating, this number rose to four, with two more CNSs (liquid hydrogen at 20 K and solid methane at 50 K) at ISIS TS-2. ISIS TS-2 uses 20% of the proton pulses produced by the ISIS accelerator, so the corresponding beam power is ~32 kW. Another short pulse spallation source started operating in mid-1980s, the Manuel Lujan, Jr., Neutron Scattering Center at the Los Alamos National Laboratory, USA, with similar beam parameters to the ISIS Neutron and Muon Source, UK. Although most accelerator based neutron sources for neutron scattering are pulsed, there is also a steady state spallation source, SINQ, at Paul Scherrer Institute, Switzerland, where a liquid deuterium cold moderator has been in operation since 1996. The proton beam energy is 590 MeV and beam current is ~1.2 mA (~600 kW beam power).

The subsequent decrease in the number of CNSs produced in the 1990s and in the first decade of the new century can be explained as follows:

(a) Commissioning of new reactors was slower than the rate of decommissioning of old ones;
(b) Security standards for CNSs at reactors have been significantly tightened, especially after the Chernobyl disaster. Additional technical solutions became demanded for CNSs;
(c) Large CNSs installed at reactors with high heat dissipation require powerful cryogenic systems to maintain the moderator at low temperatures;
(d) There are requirements for complete automation so that the operation of the reactor can be independent of the status of the operation of the CNS.

The next significant period is related to the start of operations in 2007 of the Spallation Neutron Source at Oak Ridge National Laboratory, USA with a beam power at the level of 1.4 MW and the Japanese Spallation Neutron Source's 1-MW pulsed spallation neutron source at J-PARC in 2008. There is a number of new spallation sources planned to be operational during the next decade: the short pulse spallation source in China (the China Spallation Neutron Source) and the Second Target Station at Oak Ridge's Spallation Neutron Source, where the focus will be on cold neutrons production, as well as the long pulse European Spallation Source near Lund, Sweden.

[5] Currently available at https://view.officeapps.live.com/op/view.aspx?src=http%3A%2F%2Fwww.ottosix.com%2Fdownload%2Fcns_world_directory2007.doc&wdOrigin=BROWSELINK.

TABLE 2. HISTORICAL LIST OF COLD NEUTRON SOURCES AT RESEARCH REACTORS

Reactor, location	Country	Start	MW	Moderator	Reflector	Flux	Reactor status	Refs
BEPO, Harwell	UK	1956	6	LH_2.	graphite	0.015	Under Decommissioning	[28]
BR-1, Mol	Belgium	1960	4	LH_2	graphite	0.02	Operational	[29]
DIDO, Harwell	UK	1960/ 1967	15/ 27	LH_2/ D_2	D_2O	2.3	Under Decommissioning	[30–31]
EL-3, Saclay	France	1962	17	LH_2/D_2	graphite	1.0	Decommissioned	[32–33]
SILOETTE, Grenoble	France	1964	0.1	LD_2	H_2O/Be	0.01	Decommissioned	[34–35]
FiR-1, Espoo	Finland	1964/ 1972	0.25	LH_2/ CH_4	graphite	0.1	Under Decommissioning	[36]
HERALD, Aldermaston	UK	1966	6	LH_2+D_2	Be	0.57	Decommissioned	[37]
AVOGADRO, Saluggia	Italy	1969	1	LC_3H_8	graphite	0.27	Decommissioned	[37]
FR-2, Karlsruhe	Germany	1969	44	LH_2	D_2O	1.0	Under Decommissioning	[38]
FRJ 2(1), Jülich	Germany	1969	23	LH_2	D_2O	2.5	Under Decommissioning	[39]
IR-8, Moscow	Russian Fed.	1970	5/8	LC_3H_8	Be	2.5	Operational	[40]
Jeep 2, Kjeller	Norway	1972	2	LH_2	D_2O	0.2	Permanent Shutdown	[41]
ILL HFR(1), Grenoble	France	1972	58	LD_2	D_2O	15	Operational	[42]
Triga Mk II, Ljubljana	Slovenia	1971/73	0.25	LCH_4	graphite	0.1	Operational	[37]
GALILEO GALILEI, Pisa	Italy	1974	5	LC_3H_8	H_2O	0.36	Decommissioned	[37]
DR 3, Risoe	Denmark	1975	10	scH_2	D_2O	1.4	Under Decommissioning	[43]
HFBR, Brookhaven	USA	1980	60	LH_2	D_2O	5.5	Under Decommissioning	[44]
WWR-M, Gatchina(1)	Russian Fed.	1980	18	LH_2	Be	4.0	Extended Shutdown	[45]
ORPHEE(1,2), Saclay	France	1980	14	LH_2	D_2O	3.0	Permanent Shutdown	[46]
FRJ 2(2), Jülich	Germany	1985	23	LH_2	D_2O	2.5	Under Decommissioning	[47]
WWR-M, Gatchina(2)	Russian Fed.	1985	18	$LD_{2\ +(40\%)}\ LH_2$	Be	4.0	Extended Shutdown	[48]
KUR, Kyoto	Japan	1987	5	LD_2	graphite	0.6	Operational	[49]
ILL HFR(2), Grenoble	France	1987	58	$LD_{2\ +(10\%)}\ LH_2$	D_2O	15	Operational	[49]
NIST NBSR(1) Gaithersburg	USA	1987	20	$D_2O + H_2O$ 8% ice	D_2O	2	Operational	[50]
Triga Mk II, Ithaca	USA	1988–90	0.5	mesitylene	D_2O	0.03	Decommissioned	[37]
FRG 1, Geesthacht	Germany	1988	5	scH_2	Be	1.3	Under Decommissioning	[51]
FRM, Garching	Germany	1988	4	scH_2	Be/H_2O	0.8	Under Decommissioning	[52]
HWRR, Beijing	China	1988	10/15	LH_2	D_2O	2.4	Under Decommissioning	[53]
JRR-3M, Tokaimura	Japan	1990	20	LH_2	D_2O	0.3	Operational	[54]
HOR, Delft(1)	Netherlands	1990	3	LCH_4	H_2O	0.29	Operational	[55–56]
NETL, Triga Mk II, Austin	USA	1991	1	mesitylene (40 K)	graphite	0.27	Operational	[57]

TABLE 2. HISTORICAL LIST OF COLD NEUTRON SOURCES AT RESEARCH REACTORS (cont'd).

Reactor, location	Country	Start	MW	Moderator	Reflector	Flux	Reactor status	Refs
BER-II, Berlin	Germany	1992	10	scH_2	Be	2	Permanent Shutdown	[58]
MURR, Columbia	USA	1994	30	LH_2	Be	6	Operational	[59]
IBR-2M, Dubna(1)	Russian Fed.	1994	1.5	sCH_4	H_2O	0.1	Operational	[60]
NIST NBSR(2), Gaithersburg	USA	1995	20	LH_2	D_2O	2	Operational	[61]
HFIR, Oak Ridge	USA	1999	85	scH_2	Be	21	Operational	[62–63]
WWR-M, Gatchina(3)	Russian Fed.	1999	18	SD_2	graphite	0.13	Extended Shutdown	[64]
BRR, Budapest	Hungary	2000	10	LH_2	Be	2.5	Operational	[65–66]
NIST NBSR(3), Gaithersburg	USA	2002	20	LH_2	D_2O	2	Operational	[67]
TRR-2, Lungtan, Taiwan	China	2002	20	LH_2	D_2O	2.7	Operational	[68]
FRM-II, Garching	Germany	2005	20	$LD_2/5\%H_2$	D_2O	8	Temporary Shutdown	[69–70]
OPAL, Lucas Heights	Australia	2007	20	LD_2	D_2O	3	Operational	[71–72]
CARR, Beijing	China	2009	60	LH_2	D_2O	8	Operational	[73–74]
CMRR, Mianyang	China	2009	20	LH_2	D_2O	3	Operational	[75]
HANARO, Daejeon	Rep. Korea	2009	20	LH_2/D_2	D_2O	4.5	Operational	[76–77]
IBR-2M, Dubna(2)	Russia Fed.	2011	1.5	mesitylene/*m*-xylene	H_2O	0.1	Operational	[78]
PSBR, State College	USA	2023*	1	mesitylene	D_2O	0.3	Operational	Annex I, II
HOR, Delft(2)	Netherlands	2023/4*	2.3	LH_2	H_2O, Be	0.4	Operational	
NIST NBSR(4), Gaithersburg	USA	2024*	20	LD_2	D_2O	2	Temporary Shutdown	
RA-10, Buenos Aires	Argentina	2025*	30	LD_2	D_2O	3	Under Construction	

Note: L = liquid, S = solid, sc = supercritical.
Numbers in parentheses in the first column refer to specific generations of CNS.
Flux is the maximum steady state reactor thermal flux in units of 10^{14} $cm^{-2} \cdot s^{-1}$.
Start represents the in-service date of the CNS.
*Expected in-service date

2.2. MODERATOR MATERIALS

Efficient moderator materials for CNSs require a high hydrogen (H or D) content and a large vibrational density of states of the intrinsic molecular excitations in the compound in the energy range appropriate to effectively transfer kinetic energy from 'incoming' neutrons to the moderator material in order to effectively 'cool' the neutrons to the cryogenic temperature of the moderator. This has to occur without excessive absorption of the neutrons and without decomposing the moderator material. The presence of an optimal set of properties (high value of ξ (Eq. 3), large scattering cross section, small absorption cross section) and low boiling point (20.4 K at atmospheric pressure) of hydrogen, naturally determines that the following materials are used as cold moderators: liquid hydrogen and deuterium (especially in high power research reactors) and solid or liquid hydrocarbons (mostly at accelerators and lower powered research reactors).

2.2.1. Liquid hydrogen and liquid deuterium moderators

Hydrogen and deuterium are not subject to polymerization due to radiolysis, and in this regard, they have an obvious advantage over hydrocarbon moderators. At the same time, the absorbing and moderating characteristics of hydrogen (cf. deuterium) demand the optimization of the thickness of the liquid layer to obtain the most efficient source.

The hydrogen (deuterium) molecule comes in two different nuclear spin isomers (Figure 3). The cross sections of the two isomers have significant differences that are important for liquid hydrogen cold moderators. One isomer, called para (*p*-), is the spin-0 singlet ($1/\sqrt{2}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$), and the other, called ortho (*o*-), is the spin-1 triplet $\{|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle, (1/\sqrt{2}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)\}$. There is an energy difference (14.7 meV, equivalent to ca. 170 K) between these two isomers in hydrogen. At high temperatures (room temperature) the distribution of isomers of hydrogen approaches 25% *p*-, 75% *o*-. At temperatures far below 170 K, typical of liquid hydrogen moderators, the equilibrium distribution approaches 100% *p*-hydrogen. Some practical engineering aspects concerning the spin isomers are discussed in Section 4.3.2 and some of the scientific developments are discussed further in Section 11.2.

Most of the first CNSs using liquid hydrogen created at research reactors were made in the form of disks with a diameter of 15–20 cm and thickness of 5–7 cm. They were located in the radial or tangential channels of the reflector of the reactor. Their measured gain factors as a function of the neutron wavelength were determined as the ratio of the fluxes at the exit of the channel with and without hydrogen in the chamber. The isomer ratio in these sources was never directly determined. In Figure 4, the calculated gain factors for hydrogen in a CNS with a chamber with a diameter of 18 cm and thickness of 5 cm are also given. The measured values of the gain factors are quite close to one another and are of low sensitivity to the flux gradients and to the presence of vapour in the source.

At modern CNSs, achieving a very high proportion of *p*-hydrogen has become of paramount importance in many recent designs (Section 11.2). The implications from neutronics on the CNS design are discussed in Section 4.1.1.

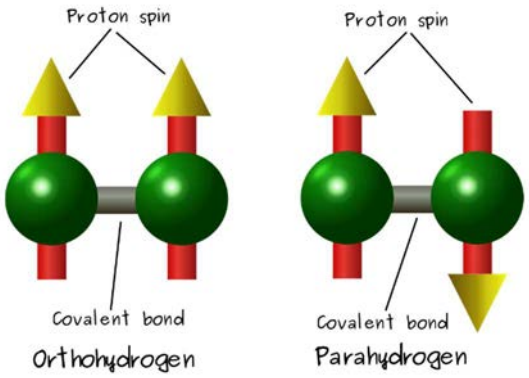

FIG. 3. Spin isomers of molecular hydrogen by Xaa is licensed under CC BY-SA 3.0 (Wikimedia Commons).

Apart from hydrogen, liquid deuterium is also a good moderator for CNSs ($\xi = 0.73$ (Eq. 3), atomic mass 2, boiling point 23.6 K at atmospheric pressure). Deuterium's scattering cross section is smaller than that of hydrogen, but the absorption in deuterium is fairly small, so it is a prerequisite to use much larger volumes (several tens of litres) of liquid deuterium. In the 1970s and 1980s, studies and optimization of CNSs at various reactors were conducted in Europe. To summarize the data of gain factors for different sources is a significant challenge since the parameters of each experiment are quite specific. Nevertheless, the comparison of the literature data made by P. Ageron et al. [79–80] provides a comprehensive picture and allows to compare different sources with different moderators (Figure 4).

The measured gain factors of deuterium sources have higher values than those obtained at hydrogen sources particularly in the long-wavelength part of the spectrum (Figure 4). The tangential or radial placement of the deuterium source also has an impact on the gain factor. The radial placement of such a source is more sensitive to the flux gradient. And the difference in the gain factor, depending on the location of the CNS, can amount to 2–2.5 times.

The optimum layer thickness of a deuterium source is at least 20 cm. Because of the large thickness of the moderator layer, the maximum cold neutron flux forms near the centre. To extract these neutrons and obtain a higher gain factor, deuterium sources can be equipped with cavities filled with He or gaseous deuterium. Such cavities can increase the gain factors with respect to the experimental channel by 2.1 times for a radial CNS and by 1.6 times for a tangential CNS. Calculations show that to obtain the maximum gain factor the cavity needs to enter the source chamber by 2/3 of its diameter. Due to the larger dimensions of a typical deuterium CNS, it may be the first choice in a research reactor based neutron source when one wants to build many instruments that need to be fed by many cold neutron guides.

If the volume of a deuterium source is insufficient to thermalize the neutron flux, mixtures of hydrogen and deuterium may need to be used. It is assumed in the first approximation that optimization calculations can be carried out using simply using the percentage of each component. In the deuterium source at the FRM-II reactor (Garching, Germany), the optimal hydrogen content was determined to be 5–10%.

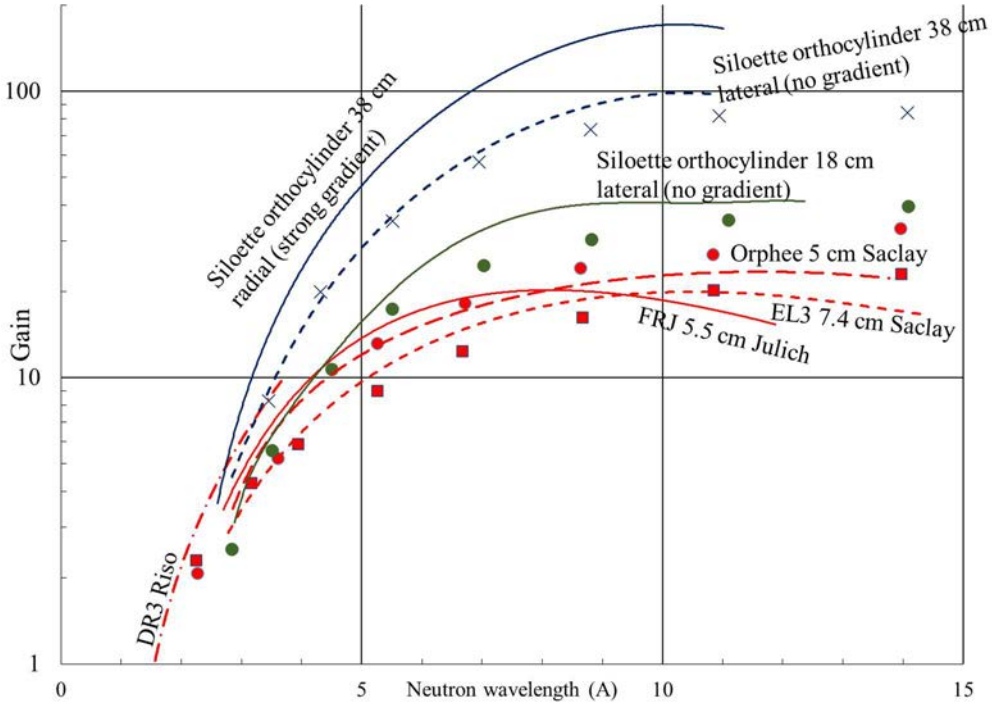

FIG. 4. Gains from a variety of liquid hydrogen and deuterium CNSs. Blue lines (measured in the Siloette reactor at Grenoble, France) and symbols (calculated for the HFR reactor at ILL, Grenoble, France) are for liquid deuterium of 38 cm diameter. The green line (measured) and symbols (calculated) are for liquid deuterium of 18 cm diameter from the Siloette reactor. Red squares are for 5 cm-thick discs of 38 cm diameter containing pure liquid p-hydrogen, and red circles those for a 50–50 mixture of liquid o- and p-hydrogen in the same container in a tangential tube at HFR. Red lines are CNS performances in various reactors. Data are interpolated from Refs [79–80].

2.2.2. Liquid and solid hydrocarbon moderators

The maximum value of the parameter $\xi = 1$ (Eq. 3), occurs when neutrons are scattered by hydrogen nuclei. For nuclei of other chemical elements, ξ is considerably smaller. From the point of view of the efficiency of cold neutron production, a source with a hydrocarbon moderator gives a slightly larger gain factor than hydrogen in the region of 4–10 Å [81]. However, this optimization is not very significant. Hydrocarbons like methane and mesitylene have been the main hydrocarbons selected and are used in pulsed neutron sources and low power research reactors, with liquid and solid methane the most common. An exception is the steady-state reactor IR-8 (Russian Federation), which used liquid propane as a moderator.

Methane has a high hydrogen density and a high density of states in both liquid and solid forms, making it an excellent moderator. Unfortunately, it suffers from radiolysis. This is a particular problem in the solid phase. The radical species that form as defects generated under irradiation become trapped and can recombine in a phenomenon called ‘burping’ [82–83]. This runaway recombination is similar in nature to the Wigner recombination of defects in graphite and is associated with the release of hydrogen gas. The pressure generated can be sufficient to damage the moderator vessel [84]. The search for other hydrocarbons that are more resistant to radiolysis has focussed on materials that contain delocalised electrons in the form of small aromatic molecules. Some of the research in this area is discussed in Section 11.2.3. Currently, mesitylene (1,3,5-trimethylbenzene, C_9H_{12}) is the most commonly used alternative to methane at accelerators and pulsed reactors, and displays better radiation resistance [85]. Annex I discuses radiolysis of this compound in a CNS at a university research reactor, which is described further in Annex II.

When choosing the moderator material, in addition to its moderating efficiency, the consequences of radiation exposure have to be taken into account. The successful use of hydrocarbon moderators in pulsed neutron sources is associated with the less severe radiation conditions, and consequent damage to the moderator, than at steady-state sources. For example, the methane CNS at the HOR steady-state research reactor (Delft, Netherlands) was in operation for only a few hours before having to be dismantled due to gumming-up (coking) of the cooling system. Here, a system with natural circulation of methane was used to cool the moderator. Apparently, only systems with forced circulation of methane, to remove radiolysis products, ought to be used for such sources. Long-term operation of a hydrocarbon CNS in any environment lets polymerized radiolysis products accumulate, which left unchecked may lead to a thermal explosion or to the gumming-up of the volume of the moderator and the connecting pipelines. (The phenomenon has been reviewed and practical guidance is given in Ref. [84].) To prevent such undesirable effects, periodic cleansing of the entire system is necessary to dissolve and remove the radiolysis products, and there is need for periodic replacement of those elements of the installation that are most contaminated by radiolysis products. The operational experience of the solid methane moderator at ISIS Facility TS-1 (Annex III) was used in the design of the new moderator on TS-2.

Very cold and ultracold neutrons lie below the range of energies typically used for materials science (Table 1). The strong scattering of VCNs at density fluctuations in a substance greatly increases the reflection of VCN from such a substance, and materials such as nanodiamonds are under investigation as reflectors. After the implementation of the methods of UCN production by hydrogen [48] and deuterium [86], production plateaued at the UCN density of 40 cm^{-3}. Alternative ways of UCN production by means of very low temperatures are being actively discussed [48, 86–93]. One of the methods under discussion is the use of a pulsed mode of irradiation with a neutron flux of solid deuterium at a temperature of liquid He ~4.5 K [88]. Another method is the use of superfluid He [89] in the mode of accumulation of UCNs in a trap [90–91] or in the converter mode, i.e., in steady-state mode [92–93]. Such sources will not be discussed in detail in this publication.

3. FEASIBILITY STUDY

As discussed in Refs [14, 16], cold neutrons have applications in diffraction from materials with large, complex structures, the study of low-frequency excitations, and certain imaging applications. Almost the only reason to install a CNS in a neutron source is to boost the flux of cold neutrons for such experiments over that which would be achieved from only a thermal moderator; i.e., to achieve the 'gain' demanded. The technical justification for a CNS, therefore, has to be based on the provision of such neutron beams for research and innovation [94, 95]. The policy maker and funding body will make a decision on funding a CNS in the national or regional interest in scientific and technical development and education. The educational value ought not to be underestimated, as every major facility of this kind around the world has trained generations of scientists and professionals.

Advantages of CNSs include high cold neutron fluxes and potentially large moderator volumes or sizes that can illuminate multiple neutron guides and accommodate many neutron scattering instruments at longer distances, facilitating a wide range of user experiments. In proposing a new CNS, it is, therefore, critical to build support from the scientific user community because it is service to this community that may justify the investment [96–99]. Thus, the feasibility study for a CNS ought to include a study of both the existing and likely future user base that demands intense cold neutron beams in the market served by the neutron source, the expected benefits that will arise from it, balanced by the estimated costs and risks of a CNS project. The identification of commercial users is highly desirable as they can greatly enhance the usefulness and sustainability of the CNS.

A CNS demands substantial financial, human, and technical resources to design, manufacture, install, operate, and maintain. Compliance with nuclear safety regulations, when applicable, can be highly demanding for the owner/operator. Budget and schedule are very much dependent on the scope of the facility that is to be built and the performance expectation. For a neutron source, not only the direct costs associated with the CNS but also those associated with the neutron guides, neutron scattering instruments, and guide hall need to be considered to deliver the expected benefits to the user community. Some of the considerations in setting up such a facility are described in Ref. [96]. An approach to build such facilities in multiple stages with incremental and achievable milestones can be easier to manage. The feasibility study for the OYSTER cold source at TU Delft, Netherlands, described in Refs [94, 100], followed the milestones recommendations given in Ref. [96].

A new CNS at a research reactor or a spallation source is a major piece of research infrastructure requiring substantial capital and operational investments. The creation of a powerful CNS may be expected to take on average about five to six years from the beginning of design work to its commissioning. Annex IV provides the case study of the CNS at the large HANARO research reactor in the Republic of Korea. Smaller research reactors, such as university-based facilities could consider smaller cold sources that are not placed in core, but rather at the end of a beam tube, and may consider using mesitylene as the moderator material in place of liquid hydrogen or liquid deuterium (see Annexes I–II). Costs of CNSs may be significantly lower at such reactors and at CANS.

3.1. GENERAL CHOICES

Most of the currently operational research reactors with a CNS are multi-purpose. The advantage a multi-purpose reactor has of having the potential to generate commercial income from neutron irradiation services is an attractive factor for policy makers and funding bodies.

The relationship between the irradiation services and the CNS-enabled neutron science has to be seen as complimentary because high reliability and availability are the common objective even though maintenance and scheduling needs may conflict from time to time. Commercial income from a multi-purpose reactor does not cover all the costs of reactor operation, even ignoring capital, decommissioning, and management of spent fuel and radioactive waste costs. By recognizing and leveraging the strategic values of all facilities at the reactor, the facility owner can ensure their productivity and longevity.

A CNS may be an integral part of the reactor design from the beginning (e.g., the Open Pool Australian Lightwater (OPAL), Australia; HANARO, Republic of Korea; China Advanced Research Reactor (CARR), China; Forschungsreaktor München II (FRM II), Germany). The other possibility is that a new CNS can be retrofitted into an existing research reactor. This happened at the NIST reactor, Gaithersburg, USA; HFIR, Oak Ridge, USA; Delft, Netherlands; Budapest research reactor, Hungary; and BER-II reactor, Berlin, Germany. Descriptions of the requirements and subsequent design of the retrofitted CNS in the BER-II reactor, Berlin, Germany are given in Ref. [101], and the experience in the development of CNSs at the WWR-M reactor, Petersburg Nuclear Physics Institute, Russian Federation, and of the first CNS installed in the Budapest reactor are given in Ref. [102]. To retrofit a CNS on an existing major research reactor is not only a major modification to the reactor but also demands more space outside the reactor building to accommodate new neutron guides and instruments.

A research reactor is subject to nuclear safety regulation and is, therefore, more vulnerable to administrative challenges and the general public's reaction to any abnormal events than a spallation source. On the other hand, to build a spallation source based CNS is to make a long term commitment to a powerful, yet essentially single-purpose, platform for neutron science, which is a significant undertaking in both initial capital and ongoing budgetary support for operations, expansion, and upgrade of the neutron scattering instruments required to meet the future user demand. Examples include the Japan Proton Accelerator Research Complex (J-PARC), Japan; the Spallation Neutron Source (SNS), USA; the ISIS facility, UK; China Spallation Neutron Source (CSNS), China; Paul Scherrer Institute (PSI), Switzerland and the European Spallation Source (ESS), Sweden. Compact accelerator based neutron sources are generally far cheaper and offer more flexibility in using and modifying CNS systems. Most CANS are dedicated to one or two goals and produce lower neutron primary energies with lower source strength (n/s). Examples of CANS in which CNS development has been conducted include systems at RIKEN and Hokkaido University, both in Japan. These are good facilities to train scientists and engineers as well as to conduct research [14] .

3.2. KEY PERFORMANCE INDICATOR

As a key performance indicator, a gain factor is estimated, which is defined as the ratio of the fluxes of cold neutrons at the inlet of neutron guides with the CNS to that without it (see Section 2.2). A realistic objective is not to find the maximum possible gain factor, but a gain factor optimized over the physical, engineering, and financial constraints of the project. The gain factor of the CNS is a function of its location in the reactor, moderator material, operating temperature, geometry, and configuration of the supporting structures such as beam tubes and in-pile neutron guides. The gain factor is calculated at first to provide guidance to the design. After the new CNS is installed, the gain factor achieved may be measured if a suitable location can be found, for example, at the reactor face. The comparison between the calculated and measured values provides valuable data to understanding the performance of the CNS installed, including benchmarking the calculations. From the viewpoint of the project's customers, the

neutron beam users, what matters is the cold neutron flux delivered to their samples on the neutron scattering instruments as well as the reliability and availability of the CNS.

Another parameter that is of great performance in the design of moderators for pulsed sources is 'brightness'. The brightness (or 'brilliance') of a neutron source can be defined as the number of neutrons of defined wavelength (or energy) per unit of wavelength (or energy) that are emitted through a unit area within a unit of time and travelling within a unit solid angle. Figure 5 shows the pulse shape of cold (5 Å; 3 meV) neutrons emitted from the ISIS TS-2 solid methane moderator, a short-pulse CNS, where the maximum value of the time-profile (around 6×10^{12} $cm^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot Å^{-1}$) is the peak brightness (for a proton beam energy of 800 MeV and beam current of 40 μA).

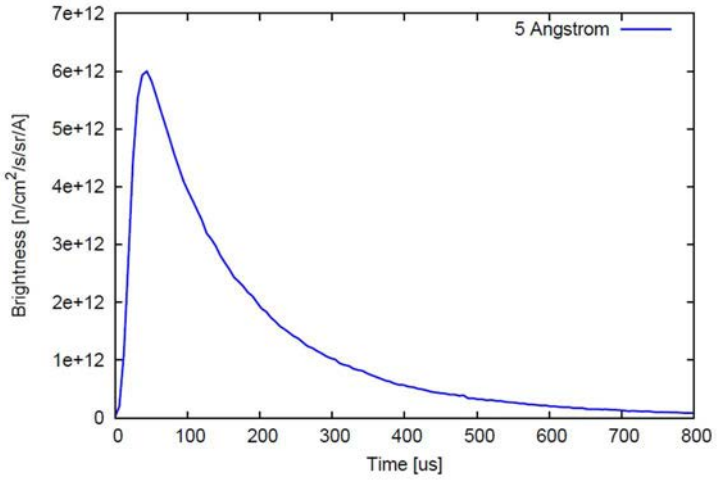

FIG. 5. The pulse shape of cold (5 Å, 3 meV) neutrons emitted from the ISIS TS-2 methane moderator (courtesy of G. Škoro, ISIS Facility).

The integral under the curve in Figure 5 multiplied by the proton beam repetition rate (10 pulses per second in this case) is the time-averaged brightness. If this procedure is performed for a set of wavelengths, the time-averaged brightness as a function of neutron wavelength can be obtained as shown in Figure 6.

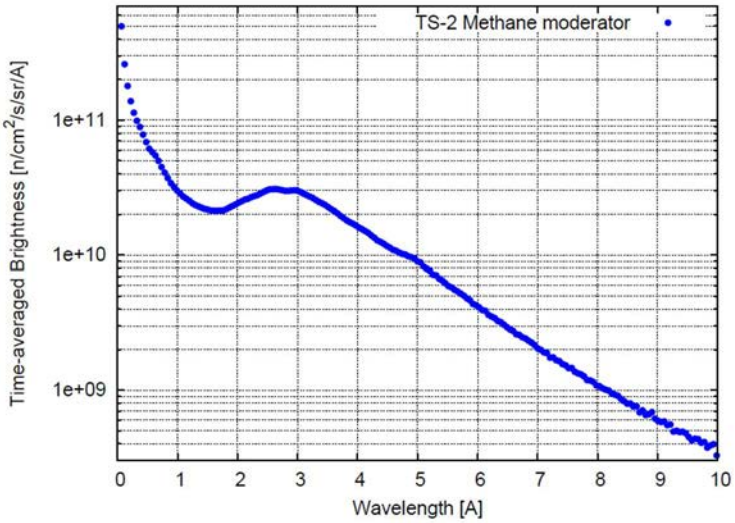

FIG. 6. Time-averaged brightness of the ISIS TS-2 methane moderator as a function of neutron wavelength (for a 40 μA, 800 MeV proton beam at 10 Hz repetition rate (courtesy of G. Škoro, ISIS Facility).

For a long-pulse facility, like the ESS, the connection between peak and average brightness is different than the case of short-pulse facilities (where proton pulse length is significantly shorter than the characteristic neutron moderation time). For example, the peak brightness B_p in the ESS case is defined as: $B_p = B_a/(f \cdot \tau)$ where B_a is time averaged brightness, f is beam repetition rate, and τ is pulse length. Finally, for steady state neutron sources the peak and time-averaged brightness values are identical. Table 3 shows the characteristics of the different pulsed and continuous neutron sources as well as their peak and average brightness for cold neutrons, defined for this table as $\lambda > 5$ Å, $E < 3$ meV.

TABLE 3. CHARACTERISTICS OF SOME CNS (PULSED AND STEADY STATE)

Source	Power (MW)	Rep rate (Hz)	Peak brightness ($cm^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot Å^{-1}$)	Average brightness ($cm^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot Å^{-1}$)
ISIS TS-1	0.128	40	2.7×10^{12}	1.4×10^{10}
ISIS TS-2	0.032	10	5.0×10^{12}	7.7×10^{9}
SNS-FTS (2019)	1.4	60	1.2×10^{13}	2.5×10^{11}
SNS-FTS	2	45	3.0×10^{13}	3.5×10^{11}
SNS-STS	0.7	15	3.6×10^{14}	1.1×10^{12}
J-PARC	1	25	6.0×10^{13}	3.5×10^{11}
ESS	5	14	1.2×10^{14}	5.0×10^{12}
ILL	57	CW	2.7×10^{12}	2.7×10^{12}
FRM-II	20	CW	1.7×10^{12}	1.7×10^{12}

Note: Brightness is calculated at 3 meV (5 Å). For each neutron source, the moderator with the highest brightness for the stated energy/wavelength has been chosen (except for ISIS TS-1 and TS-2 where values for hydrogen moderators have been listed).

As noted above, the most important thing during design and optimization of the neutron source is to relate the source brightness and neutron flux on sample. In other words, the 'transfer' of neutrons from the moderator to the sample is of critical importance. More details about the design and optimization are given in the Section 4.1.

3.3. PRACTICAL CONSTRAINTS ON MODERATOR MATERIALS

The choice of the moderator material depends on a number of factors: quality of the cross section data at low temperatures, wavelength of interest, location, and volume restrictions (whether it is a retrofit or a new design), interface with cold neutron beam and guides, thermohydraulic feasibility, limitation of refrigeration capacity, safety case requirements, operational and maintenance demand, replacement provision and route of disposal subject to design lifetime. The moderator choice is part of the neutronic design, which has to be conducted in conjunction with the thermohydraulic design. The most common moderators are liquid hydrogen and liquid deuterium, especially at reactors. Due to radiolysis, solid methane, mesitylene, and triphenylmethane have also been used, chiefly at accelerators and lower powered reactors.

The CNS moderator is heated by neutron and γ radiation and, therefore, has to always be cooled during operation to avoid undesirable phase changes (Section 4.2). Blackbody radiation heating due to the large temperature differential between the CNS at cryogenic temperature and the surrounding environment at room temperature (or higher) has to be considered, as well as conductive heating. In steady state, heat removal is equal to heat generation in each component or material. The thermohydraulic design needs to be conducted in conjunction with the neutronic design (Section 4.4). A key parameter for liquid moderators where boiling is taking place is the void fraction. The thermohydraulic design has to ensure the coolant can reliably remove heat from the CNS, so that the anticipated void fraction does not exceed any neutronic design requirements. The heat exchange can be effectively designed using either natural circulation or forced convection.

Helium is almost universally chosen as the coolant because of its low boiling point, chemical inertness, negligible neutron activation, and commercial availability. Natural convection of the moderator has been used by most existing CNSs because of its simplicity. Forced convection of the moderator may generate more effective cooling and deliver better neutronic performance, but it is technically more demanding than natural circulation and would pose more challenge to the safety case if hydrogen or deuterium is pumped. Structural materials (Section 4.5) used in the thermohydraulic design inevitably absorb cold neutrons and therefore have to be modelled in the neutronic design for verification. It is an iterative process.

3.4. EXTERNAL REVIEW

It is prudent to involve experts from outside the host organisation to review the CNS project. However, there is not a one-size-fits-all formula to conduct such a review. Some projects have a panel of experts that review the project progress at a high level at regular intervals throughout its life. In other circumstances, experts can be used to review specific topics, such as selecting the concept at the planning stage, finding the solution to an engineering challenge during the design phase, or reviewing the integrity of the safety case before submission for regulatory approval. It is wise for the host organisation to get help in its weakest areas, and only pay for external oversight and for specific expertise that is not already in-house.

4. DESIGN

First and foremost, the objective for designing a CNS is to make it as bright as feasible in the cold neutron energy range, subject to project constraints, so it can illuminate as many neutron instruments as possible at a satisfactory flux level. Many compromises are to be expected because of constraints in budget, system complexity, operational requirements, safety, and material lifetime under irradiation. The design of a CNS is an iterative process of combining and optimising considerations in neutronics, thermohydraulics, material science, mechanical and process engineering, as well as integration with the physical structure of the reactor or accelerator, and its control and safety systems. Safety and licensing requirements are so important that they need to be taken into account from the very beginning.

4.1. NEUTRONICS

Neutronics calculations are always a first and an extremely important step. In a very narrow sense, one could say that the goal of neutronics calculations is to find the optimal parameters of the moderator which will give the best performance of the CNS subject to the project constraints. As an illustration of the difficulty of the task, it is sufficient to mention that the neutron energies before slowing down are at the level of MeV, or even higher, and after slowing down they have to be at level of meV, or below (see Figures 1–2). This means that particle transport/interactions have to be precisely simulated over nine (or more) orders of magnitude.

The interactions of neutrons can be modelled using different Monte Carlo codes with the corresponding cross section libraries[6] such as the Evaluated Nuclear Data File[7] (ENDF) [103] and other general and special purpose libraries. The transport of high energy neutrons is particularly important for simulations of accelerator based neutron sources. MCNP6/MCNPX[8] [1] is currently the most frequently used Monte Carlo code for full simulations of neutron production (and other various particles) and neutron slowing down processes down to the thermal and cold energy regions. For induced activation calculations, it can be combined with 'inventory codes' such as CINDER'90 [1]. Other codes that are used include Geant4[9], PHITS[10], and FLUKA[11]. The neutronics modelling also has to provide the data for the engineering design of the source, so not only the data relevant for neutron experiments (for example, neutron spectrum and time pulse shape) have to be accurately modelled, but the precise estimate of the energy deposition and radiation damage in the cold source components is also of crucial importance. In what follows, the overview of the most important governing parameters of a neutron source, from the neutronics point of view, is presented. More details about the neutronics designs and optimizations of a typical pulsed CNS are given in Annex III.

4.1.1. Cold moderator neutronics

The role of a cold moderator is to slow down neutrons produced from a target (in the case of an accelerator based neutron source) or fuel (in the case of a research reactor) to the very low energies needed for neutron beam experiments. The moderators are the most important component of a neutron source that determine the final performance of the source. Cryogenic moderators at temperatures from a few K up to 150 K are used to obtain high intensities in the cold neutron region [106, 107]. For most of the moderator materials, there are sets of

[6] Cross Section Evaluation Working Group (CSEWG), https://www.nndc.bnl.gov/csewg/.
[7] Evaluated Nuclear Data Library Descriptions, https://www.oecd-nea.org/dbdata/data/nds_eval_libs.htm.
[8] The MCNP Code, https://mcnp.lanl.gov/.
[9] Geant4, A simulation toolkit, https://geant4.web.cern.ch/.
[10] PHITS, Particle and Heavy Ion Transport code System, https://phits.jaea.go.jp/.
[11] FLUKA, http://www.fluka.org/fluka.php.

corresponding scattering kernels describing the interactions of neutrons in the thermal and especially in the cold energy regions.

Liquid deuterium (D_2) and liquid hydrogen (H_2) are the standard choice of cold moderator materials in research reactors. Molecular hydrogen exists in two spin isomers *o*-hydrogen and *p*-hydrogen (Section 2.2.1), and the energy difference between the two isomers is 14.7 meV. The isomer has significant influence on the neutron scattering cross sections from hydrogen in this energy region, as the neutron and proton nuclei can exchange spin. As illustrated in Figure 7, at neutron energies greater than 0.1 eV, the cross sections of both isomers are practically identical. When the energy of the neutron is lower than 0.1 eV, the *p*-hydrogen scattering cross section decreases sharply while for *o*-hydrogen it continues to rise. Such a 'filter-like' behaviour in the cross section of *p*-hydrogen (cf. the Be filter in Figure 2), with a large cross section for the fast-incoming neutrons and a small cross section for already moderated neutrons, is very useful. Therefore, *p*-hydrogen is the preferred choice for a moderator. It enables 'low-dimensional' moderators to be constructed, for moderator chambers in forms such as rods, discs, butterflies, as once an incoming neutron is moderated to the cold range, a cold neutron can easily travel through the moderator and leave it (be emitted) with minimal risk of 'up-scattering'. However, it causes other effects, including non-isotropic emission and distinctly non-Maxwellian spectra (see Ref. [108] for further description). There are several existing scattering kernels [109–112] for neutronics calculations of liquid hydrogen moderator performance. Practically all of them are reasonably good but some improvements are needed, especially for the *p*-hydrogen cross section at very low energies.

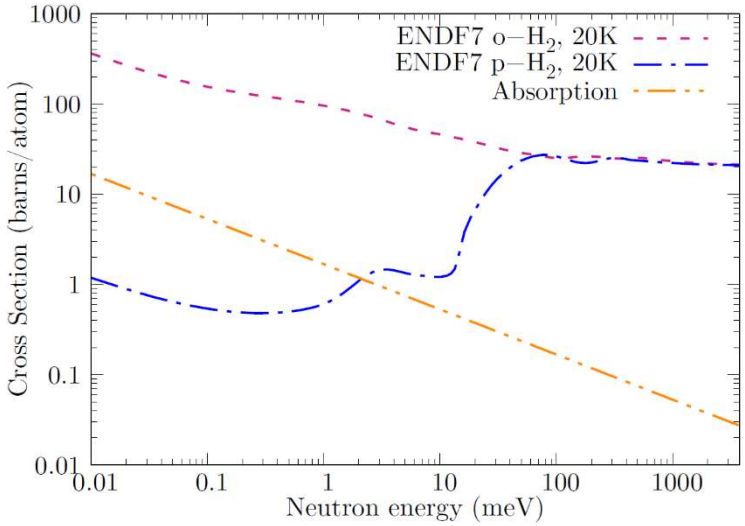

FIG. 7. Scattering and absorption cross sections for o- and p-H_2 at 20K produced from the ENDF-7 library. This figure by the authors of Ref. [113] is licensed under CC BY-4.0.

Figure 8 shows the scattering cross section for liquid *p*- and *o*-deuterium where similar (but not so dramatic) behaviour to that in hydrogen can be seen. For neutron energies below 3 meV, the scattering cross section with deuterium drops sharply.

More than 90% of CNS moderators at steady state research reactors use liquid hydrogen [114–115] or liquid/solid deuterium [116]–[118]. There are only a few reactors where hydrocarbon moderators such as liquid propane (C_3H_8) [119] or mesitylene (C_9H_{12}) [57, 120] are used. Hydrogen is a very popular moderator material but its physical properties (narrow temperature interval between melting, 14 K, and boiling, 20 K) limit its use for situations where an energy-flexible neutron source is needed. This is one of the reasons why solid mesitylene (melting

point 228 K, boiling point 538 K) is an interesting CNS moderator material, especially at pulsed reactors, such as IBR-2 at Dubna, Russian Federation. The relatively high melting point of mesitylene allows to change the temperature inside the moderating chamber (e.g., between 20 and 150 K) to tune the peak of the neutron spectrum from short to long wavelength and back. The neutron intensity from a mesitylene moderator is relatively high [121] and the radiation resistance can be further enhanced if a mixture of mesitylene and *m*-xylene (3:1 proportion) is used.

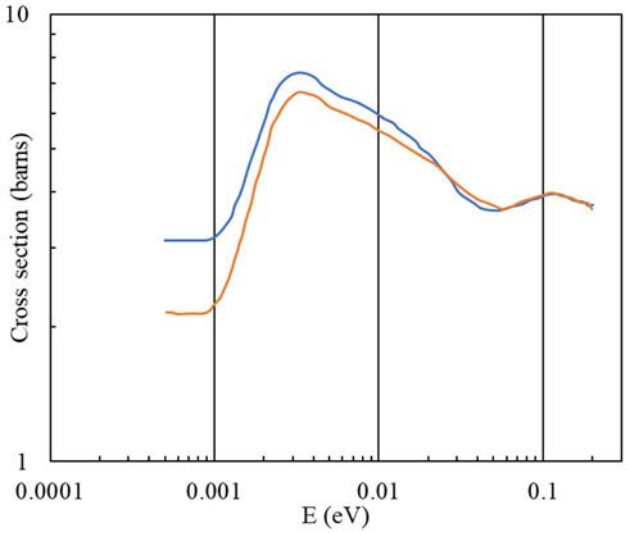

FIG. 8. Scattering cross section for liquid p-deuterium (orange) and liquid o-deuterium (blue) at 19K. Data interpolated from Ref. [122].

Hydrogen-rich moderator materials used at accelerator based sources include methane (liquid and solid), some other higher hydrocarbons and, of course, liquid hydrogen. In thermal equilibrium, the neutron intensity and pulse width are related to the moderator thickness. For example, the intensity and neutron pulse width increase with increasing moderator thickness. Therefore, to obtain a narrower neutron pulse, a thinner moderator can be used (but with a potentially significant loss of neutron intensity). In order to sort out (at least partially) this issue, moderator 'poisoning' can be used. The idea is based on inserting an absorbing material, such as Gd, into the moderator. This absorbs neutrons that have been moderated down to thermal energy region outside of the moderator chamber itself and been returned by the reflector (having spent a long time diffusing over a long path length), which would broaden the neutron pulse.

The situation is different for long pulse spallation sources [123], where the accelerator pulse is typically in the range of 1 ms, i.e., considerably longer than the response time of a cold or thermal moderator, which is in the order of 100 μs. For an accelerator-based facility, this has the considerable advantage that there is no need for a compression ring, thus reducing considerably the cost and the complexity of the accelerator. The engineering of the spallation target has also lower challenges than a short-pulse source of the same power, due to the lower peak power density deposited. The longer pulse, however, demands the use of choppers to shape the time profile of the neutron pulses for the instruments. The different concept of a long pulse spallation source has an impact on the design of the moderator. While, as in short-pulse sources, the use of liquid deuterium is not recommended (unless the time-average moderator intensity is the only parameter of interest, which can be the case for some non-scattering applications) as they need to be large to be efficient, there is no requirement for using decoupling or poisoning layers, as the time-structure of the neutron pulses is determined by the choppers. Thus, the moderator configuration in a short pulse facility and in a long pulse facility differ. In short pulse facilities, such as ISIS (TS-1 and TS-2) and J-PARC, one can find different moderators,

coupled, decoupled, or poisoned (see Section 4.1.3 for more description of decouplers and poisons) at a single facility. In a long pulse facility, such as ESS or the planned SNS TS-2, the moderator configuration is simpler, and in principle a single moderator can serve all the neutron beamlines. In the latter case, a difference can arise, depending on whether the facility is also designed to utilize thermal neutrons. If that is the case, there are constraints in the moderator design, in the sense that the design has to accommodate a wider neutron bandwidth ('bi-spectral extraction') [124–126].

At pulsed sources, a solid methane moderator shows the best moderating performance. But, as outlined earlier, because it is prone to serious radiation damage, its use at high power spallation sources is dramatically limited. This means that liquid or super-critical hydrogen become the only realistic cold moderator materials at higher beam powers. The performance of a liquid hydrogen moderator depends strongly on the dimensions of the moderator and especially on the *o*- to *p*-isomer ratio [109]. The *p*-hydrogen fraction very slowly increases naturally with time as the system relaxes but can be significantly accelerated [127] with the use of a catalyst (see Sections 4.3.2 and 11.2.2).

One important disadvantage of a liquid hydrogen moderator is its relatively low proton density, so the active search for new types of cryogenic moderator materials, such as a triphenylmethane [128], etc. for high power spallation sources is underway. Some of the research in the area is outlined in Section 11.

Similar principles in moderator design apply to CANS. There is a growing interest worldwide in such CANS [14], which are intended to support research carried out at high-power sources, as well as to offer an alternative to small research reactors [129]. Low-powered CANS are usually based on proton beams in the energy range of 2.5–20 MeV, with average currents in the range 2 mA, impinging on Be or Li targets [130–131]. These facilities offer the obvious advantages of reduced cost, which includes much more relaxed requirements on the shielding needs than for a spallation source [14, 132]. In between the smaller compact and very large spallation sources, facilities in an intermediate energy and power range are proposed, such as the Jülich High Brilliance Source [133] or the SONATE source [134]. These facilities are based on proton beams in the range 20–70 MeV at average currents 60–100 mA on Be or metal targets as Ta. Neutron fluxes in the range of 10^{13}–10^{15} $cm^{-2}\cdot s^{-1}$ are expected from such sources. Concerning the design of a CNS for such systems, the same principles apply as for high-power sources; however, the compact size of the proton beam and target can be used advantageously in the coupling of target, moderator, and reflector, in a more efficient way than for high power sources [14, 135]. Due to the smaller size, compact finger-like cold moderator systems can be installed as part of individual experimental stations [136].

4.1.2. Optimization of performance

A question that needs answering is what to use as a figure-of-merit as representative measure of the performance of a CNS. For pulsed sources, much attention has been paid to the optimization of neutron source brightness values [137–138] (see Section 3.2). This approach is based on the idea that short-pulse sources benefit from peak brightness while the steady state sources have to be optimized relative to the time-averaged brightness. A 'sort of' universal figure-of-merit [137–139] can be defined as:

$$\mathrm{FoM} = B_p^{\alpha} \times B_a^{(1-\alpha)} \tag{4}$$

where B_p is peak brightness, B_a is time averaged brightness, and α is a factor taking values between zero and one. For continuous sources $\alpha = 0$, while for short-pulse sources $\alpha = 1$. It is

interesting to note that the analysis of the ESS instrument suite performance [137] showed that the α value is ~ 2/3, as it lies somewhere between a short-pulse and a steady-state source [139]. Peak (and time averaged) brightness can be used as an 'independent' measure of cold source neutronics performance, practically completely decoupled of the instrument properties. So, this choice of figure-of-merit is completely natural in situations where the instrument suite and corresponding science requirements are not completely defined. The optimization of neutron sources is usually focused on a narrow region of neutron wavelengths (energies). For example, the work on the SNS Second Target Station at Oak Ridge National Laboratory, USA, is focused on peak cold neutron brightness while in the ESS case the figure-of-merit is proposed to be a 'bi-spectral' combination of cold and thermal brightness (see Section 11.3.4).

For reactors, after complete thermalization in the primary thermal moderator, neutrons are available only in a narrow energy range of 0.005–0.07 eV. A CNS shifts the neutron spectra to the long wavelength region. The theoretical limit of cold neutron gain is given by the ratio $\left(\frac{T_0}{T}\right)^2$: e.g., if we take T_0 = 300 K, a room temperature moderator, and T = 20 K, the boiling point of liquid hydrogen in a CNS, the limiting gain factor will be 225. At the same time, if we postulate a situation where neutrons are simply cooled at a constant density from the onset temperature of 300 K to the temperature of 20 K, the ratio of the onset neutron flux as a function of neutron energy or wavelength to the fully thermalized flux can be written as an ideal gain factor, G, depending on the energy, E:

$$G(E)=\frac{\Phi(E)}{\Phi_0(E)}=\left(\frac{T_0}{T}\right)^{\frac{3}{2}}\exp\left[-\frac{E}{\mathrm{k}}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \tag{5}$$

or as a function of wavelength:

$$\mathrm{G}(\lambda)=\frac{\Phi(\lambda)}{\Phi_0(\lambda)}=\left(\frac{T_0}{T}\right)^{\frac{3}{2}}\exp\left[-\left(\frac{\lambda_T^2-\lambda_{T_0}^2}{\lambda^2}\right)\right] \tag{6}$$

The limiting gain factor at $E \to 0$ and $\lambda \to \infty$ in this case would be equal to:

$$\left(\frac{T_0}{T}\right)^{\frac{3}{2}}=58.1 \tag{7}$$

Due to the limited size of the moderator, incompleteness of thermalization, absorption, and non-ideality of the moderators, the increase in the yield of cold neutrons is usually significantly less than the limiting values demonstrated above. However, a gain factor of around 30 can be achieved in practice. Accurate calculations of the gain factor are quite complex, requiring the solution of the transport equation with a large number of neutron energy variables and with due account for the full geometry of the reactor. For the precise calculation of the gain factor different programs based on the Monte Carlo method are used – TRIPOLI [140], THERMOS[12], OMEGA[13], MCU[14], MCNP[8] [1], etc. References [71, 80] give a detailed description of the methods for gain factor calculations for CNSs at reactors.

[12] THERMOS-OTA, https://rsicc.ornl.gov/codes/psr/psr1/psr-107.html.
[13] OMEGA, https://rsicc.ornl.gov/codes/ccc/ccc4/ccc-433.html.
[14] Monte-Carlo Universal, https://mcuproject.ru/eabout.html.

In general terms, from a CNS located in the reactor reflector, the number, N, of neutrons of a given energy, E, impinging per second on a 'target' at the end of the output neutron channel is described by the following ratio:

$$dN(E) = \Phi(M,\Omega_c,E)\, dS\, dE \frac{d\Sigma}{4\pi l^2} \tag{8}$$

where Φ is the neutron flux in the point M on the source's surface (in this case, it is assumed that the flux on the source's surface changes slightly), Ω_c – the distribution (direction) of the emitted neutrons, dS – the emitting surface (or the surface of the channel bottom), $d\Sigma$ – the 'target' surface, l – the distance between the emitting surface and the 'target'. $\Phi(M,\Omega_c,E)$ – depends on many parameters and, especially, on the reactor power level.

The gain factor can be written as:

$$G(M,\Omega_c,E) = \frac{= \Phi(M,\vec{\Omega_c},E)}{= \Phi_0(M,\vec{\Omega_c},E)} = \frac{dN(E)}{dN_0(E)} \tag{9}$$

where Φ_0 is the flux in a point M, for Ω_c, and E, and dN_0 the number of neutrons impinging on the 'target' without the CNS. In calculations, the reactor power level has to be the same both with the CNS and without it. Usually for the optimization of the CNS in the initial calculations of the Maxwell spectrum distribution, $\Phi(M,\vec{\Omega}_c,E)$, simplified models are used, and the final calculation is made for the real geometry. The gain factor then obtained characterizes the installation with all its design elements, which influence the spectrum and the flux value.

4.1.3. Reflector neutronics

The role of a reflector is to increase neutron intensities by reflecting neutrons towards the moderator. The candidate reflector materials are those which have large scattering cross sections: graphite, D_2O, Be, Pb, Fe, Ni, Cu, etc. One can distinguish between non-moderating reflectors (e.g., Pb), and moderating reflectors (e.g., D_2O, Be). At some reactors, heavy (or light) water is used as a reflector and coolant at the same time. An interesting combination is present at the WWM-R reactor in Gatchina, Russian Federation [141], where a combination of a hydrogen chamber with deuterium surrounding it is used. At the NBSR reactor at NIST, USA, the CNS gain was doubled when the original Unit 1 was upgraded by filling the space surrounding the liquid hydrogen moderator with heavy water as a reflector (see Figure 9).

The next few sections deal mostly with reflectors at pulsed sources, i.e., they mostly pertain to spallation sources. The most frequently used reflector materials at spallation sources are Be and Pb. It has to be noted that because of the reactions induced by hadrons escaping from the target and the existence of (n, xn) reactions, neutrons may also be produced in a reflector. The coupling between reflector and moderator is very important when designing an efficient CNS. In addition, the use of a pre-moderator consisting of hydrogenous material at room temperature inserted between a cold moderator and target (Figure 10) can significantly increase the neutron intensity [142–143]. However, the price to pay for this at pulsed sources is a broader time profile for the neutron pulse, which can be detrimental for high-resolution (such as powder diffraction) experiments. As discussed in the previous subsection, regarding neutronics, similar arguments apply to the reflector for CANS as for spallation sources.

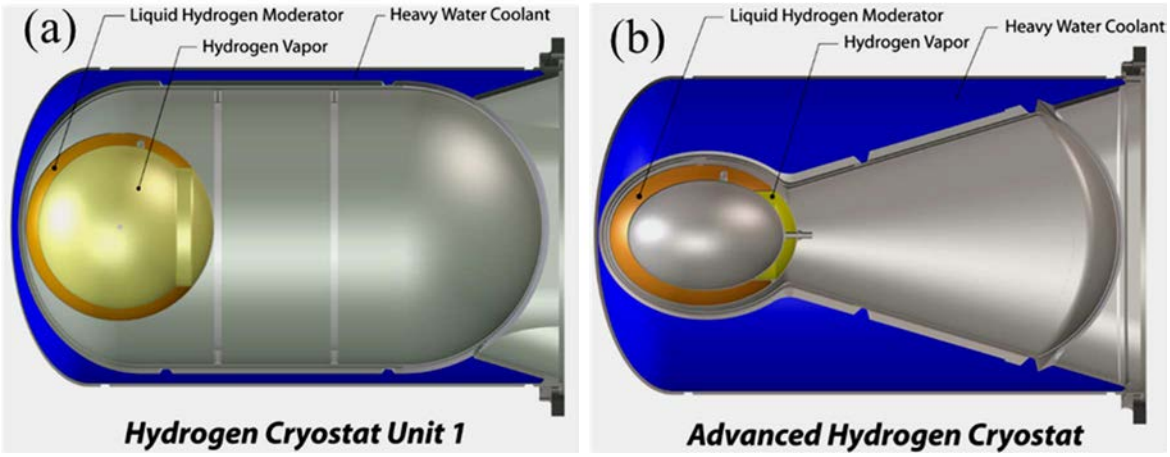

FIG. 9. Example of two liquid hydrogen cold source designs from the NSBR research reactor at NIST (a) an older version showing the cryostat in vacuum space and (b) a more modern version showing an ellipsoidal geometry of the liquid hydrogen moderator, and the addition of a significant volume of D_2O thermal moderator as reflector within the cryostat chamber. This tighter enclosure of the CNS by heavy water improved the CNS gain by a factor of two. The neutron guides (not shown) at the end of the beam tube on the right-hand side look through the hydrogen vapour to the emitting surface, mostly via vacuum. U.S. Government work.

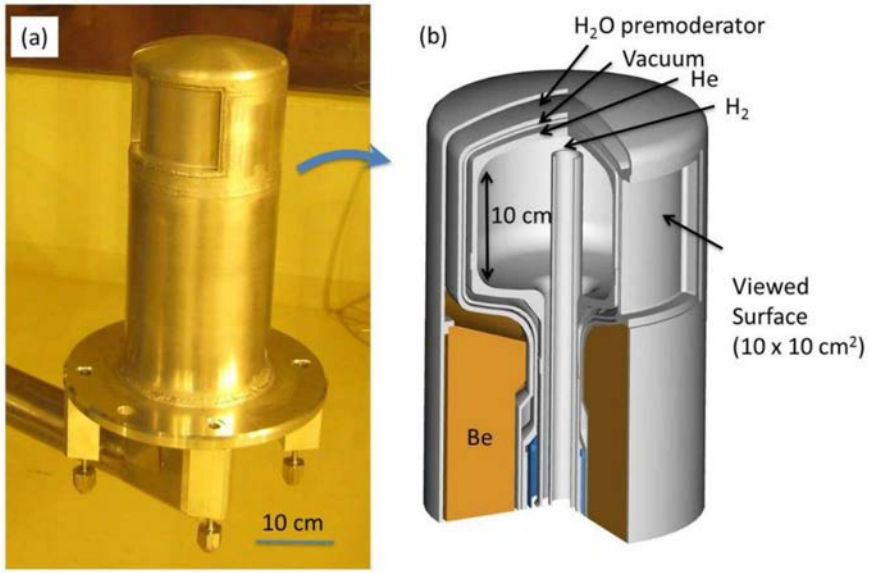

FIG. 10. View of the coupled moderator design at the J-PARC spallation source. (a) Photograph, (b) Cutaway view. A water pre-moderator layer lies outside of the vacuum insulator layer that thermally shields the CNS chamber. This figure by the authors of Ref. [145] is licensed under CC BY-4.0.

The role of 'decouplers' (slow-neutron absorbing sheets inserted between moderator and reflector except for the surface viewed by neutron guides) and flightline liners (slow-neutron absorbing sheets inserted inside the reflector flightlines) is to increase the quality of the neutron source resolution by eliminating/reducing the tail of the neutron time distribution, which results from the slow neutron scattered back from the reflector to the moderator chamber. Their use reduces the brightness of the source, but that is the price usually willing to be paid at short-pulse neutron sources. ('Poisoned' moderators include the external decoupling liner and another absorber layer set back a few cm within the moderator chamber perpendicular to its emitting surface inside the moderator chamber to further sharpen the pulse.) Figure 11 shows the decoupled moderator design of J-PARC with an Ag-In-Cd decoupler layer surrounding all surfaces of the CNS chamber except that viewed by the neutron instruments. Cadmium (Cd)

and boron carbide (B_4C) are the most widely used decoupler materials [144]. For example, boral (B_4C–Al) decouplers and liners are used in ISIS TS-1. For high-power sources, however, it is not possible to use B_4C as a liner material due to the high local heat load and, even more critically, significant radiation damage induced by the $^{10}B(n, \alpha)^7Li$ reaction. The possible solutions for this issue are to run the source without flightline liners, to use an alternative material – Cd, for example (but with significant penalties in resolution at lower wavelengths), or to develop a new type of decoupler material which could survive the high beam powers.

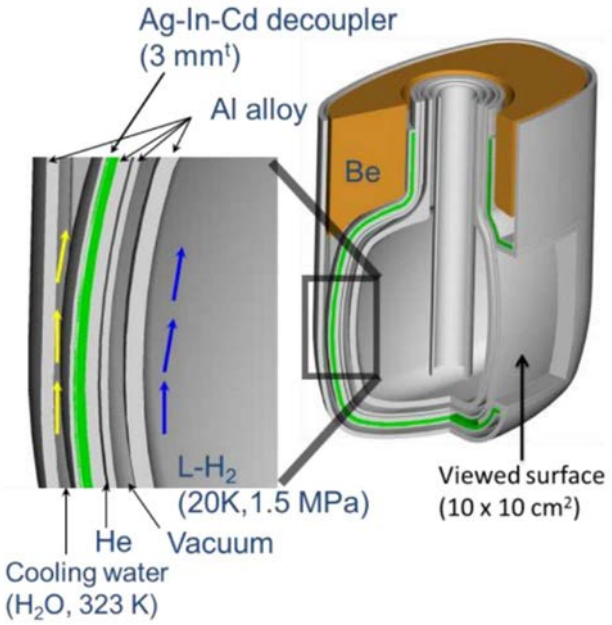

FIG. 11. View of the decoupled moderator design at the J-PARC spallation source. The Ag-In-Cd decoupling layer surrounds all surfaces of the CNS chamber except the surface viewed by the neutron scattering instruments. This figure by the authors of Ref. [145] is licensed under CC BY-4.0.

4.1.4. Moderator coupling with a neutron source

The efficient coupling of cold moderator with a reactor/target is a critical point in design of the neutron source. In the case of a reactor, there are two possible situations. When a cold moderator installation on a new reactor is planned beforehand, the neutronics design is usually straightforward. A different approach is needed if a CNS is 'retrofitted' on an already operational reactor. In this case, the presence of a CNS could lead to deterioration of the characteristics for instruments operating with thermal neutrons and influence the safety features of the reactor. So, the neutronics approach here is to optimize, for example, a combined moderator, with both water and cryogenic chambers [146].

The angular distribution of the neutrons emitted by the spallation process is practically isotropic, so finding the optimal positions of the moderators is relatively straightforward. There are three main options for target–moderator coupling: the so-called slab, wing, and flux-trap configurations. Figure 12, redrawn from Ref. [147], shows the geometries. Overviews on this subject can be found in Refs [148–150]. In wing geometry, the neutron instruments have no direct line of sight view of the target, whereas in the slab geometry they do. Flux trap designs have been used where the spallation target is split into two pieces at a point near the spallation maximum yield. The gap between them is the 'flux trap'. The moderators can be placed alongside this gap. The thesis presented in Ref. [107] describes development of the moderators at the long-pulse ESS source.

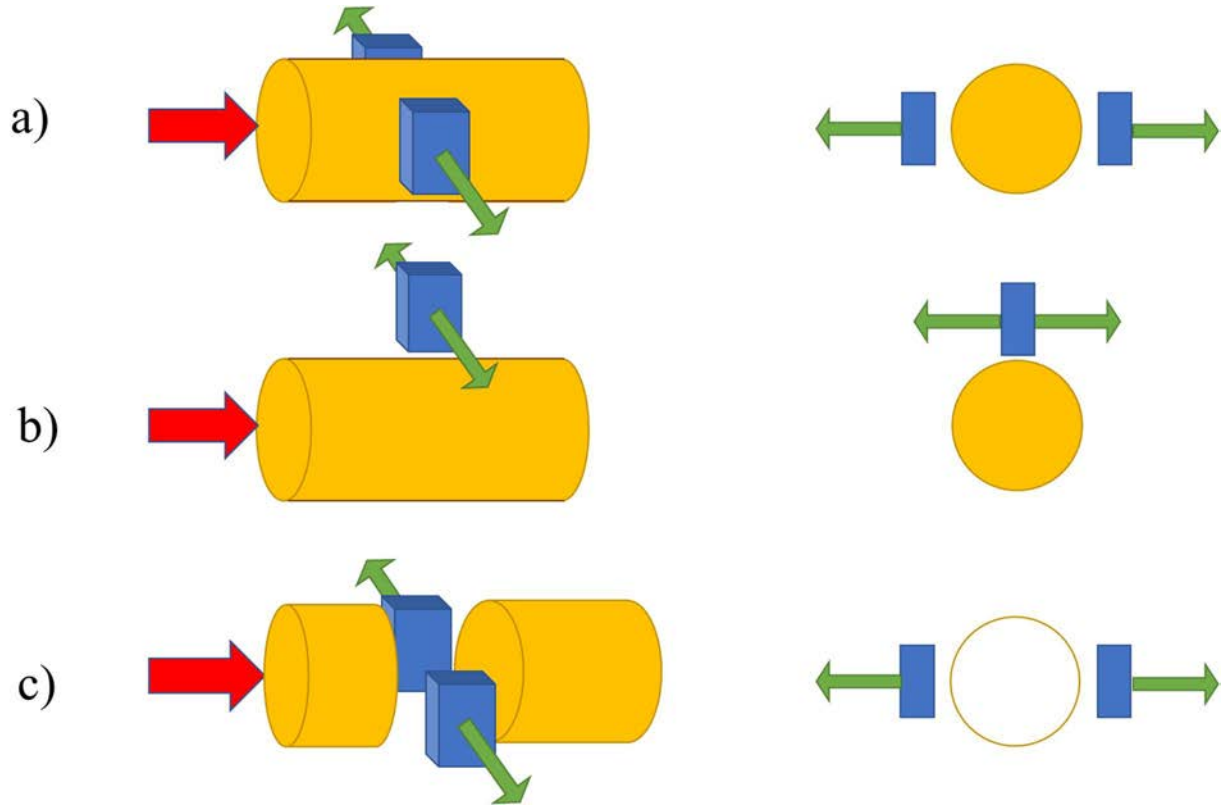

FIG. 12. Typical geometries of cold moderators and spallation targets: a) slab, b) wing c) flux trap with split target. The red arrow is the proton beam, orange the spallation target, blue the cold moderator, and the green arrow the cold neutron beam.

4.1.5. Location and geometrical constraints on the moderator chamber

The design of the moderator chamber is highly dependent on the local constraints. Considerations are based on the wavelength of interest, interface with cold neutron guides, size, and location restrictions, thermohydraulic feasibility, limitation of refrigeration capacity, safety case requirements, operational and maintenance demand, replacement provision, and route of disposal subject to design lifetime. Neutronic calculations, as explained in the previous section, are the primary driver of the design process.

A liquid hydrogen moderator is typically a few litres in volume and a few centimetres in thickness, while a liquid deuterium moderator is typically over ten litres in volume and tens of centimetres in thickness (see Figure 4). Thermal neutrons entering the CNS moderator region experience multiple scattering events to be re-moderated to the cryogenic temperature, and those cold neutrons have to be allowed to exit the moderator region freely. Therefore, the moderator chamber takes a shape that is a compromise between those two processes. Partial annular rings and disks are typical for liquid hydrogen, while liquid deuterium is mostly contained in cylinders. Re-entrant cavities are sometimes added to the cylinders to make them essentially thick partial annular rings. Figure 9 shows designs of liquid hydrogen moderators from the NIST reactor.

At a reactor there may be competing interest for the high flux positions between the CNS and other irradiation facilities. Ultimately, priorities are set by the facility owner. At other times, a retrofitted CNS can face severe restrictions in its location and dimensions. Interference to the flux profile of neighbouring facilities due to the addition of the CNS needs to be understood and estimated, especially the effects that would occur during moderator phase change.

4.1.6. Cold neutron transport

On a reactor, it is beneficial to have tangential beam tubes to the reactor core, which do not look directly at the fuel, reducing the fluxes of fast neutrons and γ rays. A Be filter 30–50 cm thick at a temperature of 100 K is essentially transparent to cold neutrons and non-transparent to thermal neutrons with $\lambda < 4$ Å (see Figure 2), and, therefore, it can be utilized to remove all thermal and fast neutrons coming from the reactor, leaving only the cold neutrons in the beam [151]. After exiting the moderator region of a CNS, cold neutrons are provided travel paths via beam tubes and neutron guides to be transported to neutron instruments. Beam tubes are empty, cooled by He if necessary, look straight into the moderator volume, and ought to be fully illuminated with cold neutrons by the CNS (see Figure 9). Cold neutrons travel through the beam tubes as if radiating isotropically from a point source. To reduce cold neutron loss, neutron guides coated with multi-layer supermirrors are employed over long distances. On some reactors, neutron guides start from inside the reactor block, although radiation damage to them has to be considered.

4.2. HEAT LOADS ON COLD NEUTRON SOURCES

The two different cases of steady state (mostly research reactors) and pulsed (mostly accelerators) are discussed in the following two subsections.

4.2.1. Steady state neutron sources

In a CNS within a research reactor, both the moderator itself and construction materials become heated due to the intense fluxes of prompt and delayed γ photons, neutrons, and β-radiation. Heat liberation depends on the position of rods, regulation, and loading of the reactor core, and can fluctuate within 20% from the nominal value. When designing a source to be manufactured from Al alloys, the delayed β radiation of the nucleus ^{28}Al ($T_{½} = 2.27$ min), formed by radiative neutron capture on ^{27}Al, has to be taken into account. The heat liberation within an Al chamber of a CNS from delayed γ photons amounts to ~10% of the input of prompt γ photons. The heat liberation in the moderator of the source depends very little on the proportion of *o*- or *p*-isomers of hydrogen. The contributions to the total heat load from the heating of the CNS's shell and the heating of the liquid hydrogen are approximately the same: at existing sources, the specific heat liberation values are 0.5–1.5 W/g and 1.4–9.2 W/g, respectively. The total heat liberation in the CNS can amount to 5.8 kW (HFR, ILL), and would have been >10 kW for the Advanced Neutron Source reactor that was planned, but not built, at the Oak Ridge National Laboratory, USA [152]. While designing the heat removal system for the CNS, the specific heat liberation value has to be taken into account, since it determines the choice of the method of cooling. Apart from nuclear heat-up, an incoming thermal heat load has to be taken into account. This is generated by thermal radiation, residual gases, and heat leaks from heat bridges and heat contacts, which, themselves, are also prone to nuclear heat-up. Such incoming heat load at existing sources amounts to 10–15% of the total heat load.

The heat load into the moderator, resulting from the spallation reaction in the target, is strongly dependent on the distance from the target and on the material that is hit. The heat input decreases almost quadratically with increasing distance from the centre of the spallation reaction. In addition, however, it also depends on the material that acts as shielding between the moderator and the centre of the spallation reaction. As a rule of thumb, it can be assumed that a high-density material increases the interaction probability, and thus more heat is deposited compared to a light material. Therefore, the heat load estimation for engineering calculations ought to include dependence on both distance and material. The functions of the stationary volumetric heat $q_{st} = f(x, y, z,$ material) ought to be fitted from the neutron simulation data. The functions

also allow an approximation of the simplified neutronic design to inform the detailed engineering design.

4.2.2. Pulsed neutron sources

In contrast to research reactor sources, most accelerator based neutron beam sources work with a pulsed accelerator. The time structure of the heat input from the spallation reaction to the CNS is pulsed and can be approximated by the accelerator pulse on the target (the worst case scenario for heat load) as a rectangular pulse, defined by a pulse repetition rate, f_p, and pulse length, L_p, which is then multiplied by the stationary approximation function, q_{st}. This results in the transient heat input $q_{tr} = q_{st}/(f_p \times L_p)$, which can lead to significantly more energy during the pulse. Therefore, the pulse-related temperature fluctuations need to at least be estimated. If the estimate is far enough away from the critical temperature (boiling, for example) a simplified steady state simulation can be performed instead of a complex transient simulation.

As an example, the average heat load in the ISIS TS-2 cold moderators (Figure 13) lies in the region 100–150 W. These values have been calculated with MCNPX assuming beam energy of 800 MeV and proton beam current of 40 μA.

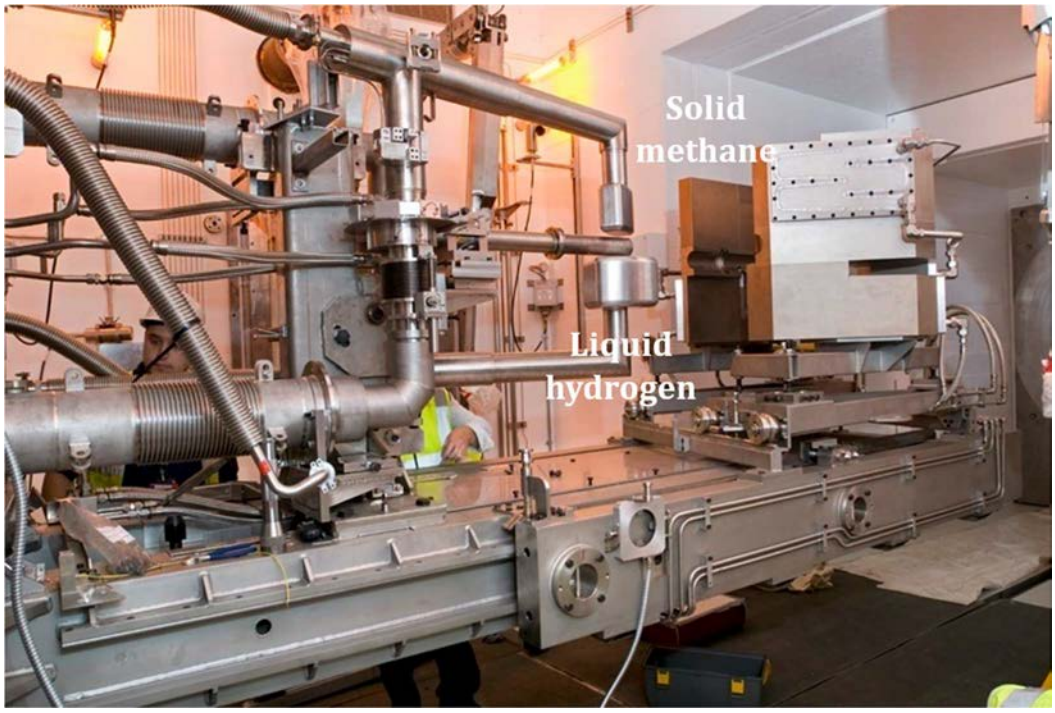

FIG. 13. A view of the ISIS Target Station 2 Target, reflector and moderator assembly showing the target (Ta-clad W cylinder), liquid hydrogen moderator, which operates at 20 K (below the target), solid methane moderator, which operates at 50 K (above the target), and the (split) Be reflector (courtesy of G. Škoro, ISIS Facility).

It is interesting to note that the average heat load in the can containing the solid methane moderator (~74 W) is slightly bigger than that in the methane/Al foam region (~60 W) in the centre of the moderator (Figure 14). The proton beam repetition rate for ISIS TS-2 is 10 Hz, and each pulse is 1 μs long. However, the heat loads in the CNS are relatively small (the proton beam power is 32 kW), so 7 g/s of He gas (direct from the fridge with a heat exchanger in the moderator) is enough to maintain temperature stability at ±0.5 K. In the case of much higher beam powers more complex transient simulations are needed (as stated above).

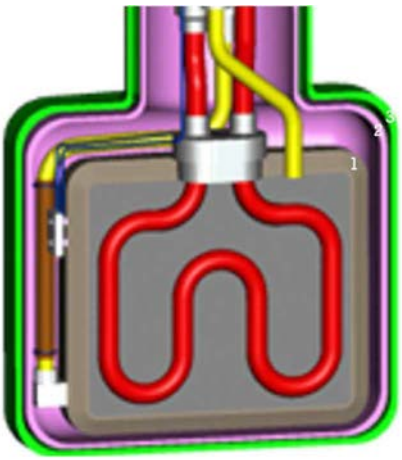

FIG. 14. A reproduction of the CAD image showing a sectional view of the ISIS TS-2 methane moderator with the Al foam and heat exchanger tube in the centre with three moderator vessel layers around (courtesy of G. Škoro, ISIS Facility).

4.3. HYDROGEN AND DEUTERIUM

When choosing the operating parameters for liquid hydrogen or deuterium, the following requirements need to be considered: expected temperature (inlet/outlet/max) to avoid changes of neutronic performance and phase changes (burnout, instability of the flow) and mechanical stresses on the moderator vessel from static and dynamic pressures. References [153]–[158] discuss this.

4.3.1. Subcritical versus boiling

To deliver the best neutronic performance, it is desirable to maintain the hydrogen/deuterium in full liquid phase or with minimal boiling. Hydrogen/deuterium has a very small temperature range in the full liquid phase, which, however, increases with increasing pressure (Figure 15). Thus, a high operating pressure is needed to avoid excessive boiling. On the other hand, by increasing the pressure, the mechanical load on the structural material increases, which demands a greater wall thickness for the vessel.

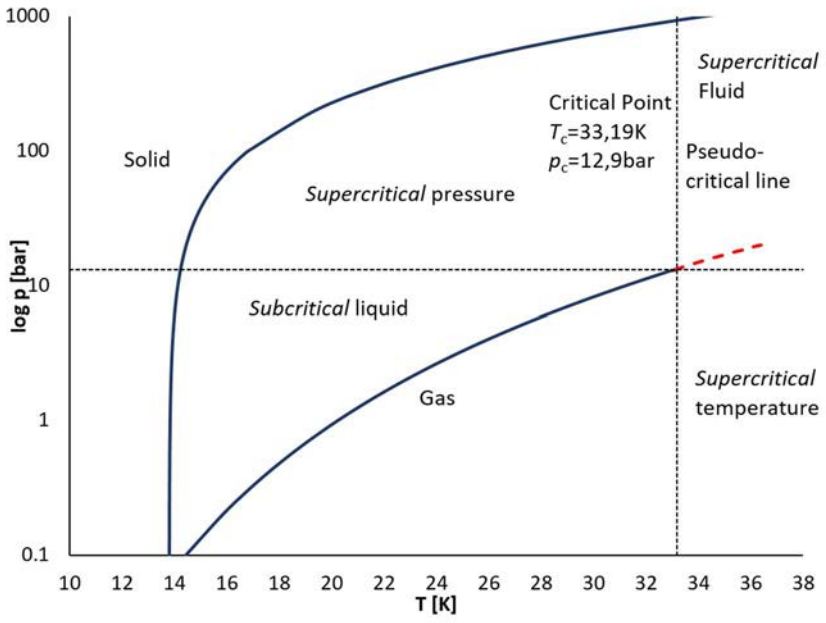

FIG. 15. Phase diagram of p-hydrogen after Ref. [153].

By providing direct He cooling to a double-walled moderator chamber as well as the heat exchanger, the CNSs at the OPAL reactor, Australia, and that at the CARR facility, China, can maintain deuterium in full liquid phase around the thermosiphon where liquid deuterium circulates by natural convection. However, such designs demand a vertical height of the thermosiphon to generate a sufficient pressure differential between the warm and cold legs. In reactors where such a height is not available, boiling may be necessary to establish natural convection by having two-phase flow in the warm leg. Reactor based CNSs rarely employ active cooling of liquid hydrogen/deuterium because hydrogen pumps add complication to the process systems.

4.3.2. Engineering perspectives on the isomers of hydrogen

For hydrogen, the natural state of equilibrium at room temperature is 75% *o*-H_2 and 25% *p*-H_2, while at 20 K it is ~100% *p*-H_2. However, the natural isomer conversion process on cooling hydrogen from room temperature to cryogenic temperature takes a very long time: on the order of months for 25% → 100% *p*-H_2. In CNSs at spallation sources, it may be critically important to maintain the hydrogen in the *p*-isomer. The conversion process can be significantly accelerated by using a catalyst, and in-situ Raman spectroscopy may be installed to monitor the isomer ratio during operation and analyse back conversion (see Section 11.2.2). From an engineering perspective, however, there is negligible difference in fluid properties between *o*-H_2 and *p*-H_2. However, the *o*→*p* conversion is associated with a substantial latent heat that is ca. 15% greater than that for vaporization at hydrogen's normal boiling point [159].

4.4. THERMOHYDRAULICS – HEAT REMOVAL METHODS

There are three major elements in the thermohydraulic consideration: moderator, coolant, and heat exchanger. The challenge is to correctly specify and place those three elements so that they can effectively remove the nuclear heat in the CNS to maintain an acceptable moderator density (i.e., minimise the void fraction due to boiling). Closed-cycle refrigerators and cold fingers can be used for small CNSs with solid hydrocarbon moderators (see Annex II). Literature review shows that the heat load generated in liquid hydrogen and deuterium CNSs can be removed by the following methods:

(a) Gaseous He at low temperature. This cools the moderator chamber through a heat exchanger combined with the chamber (tube-type heat exchangers were used in HFBR – Brookhaven National Lab, USA [44] and a source in channel B-13, PNPI – Russian Federation). The moderator operates at a higher temperature than the source chamber, ensuring heat transfer. The design has to have a minimum hydraulic resistance of the heat exchanger that allows the removal of heat from the cryogenic system by circulating He. Such an easy method of cooling has several disadvantages: additional material is introduced into the radiation zone; the thermal conductivity of the chamber material has to be high and stable under irradiation, and there is a limit of heat removal as it is not possible to develop the heat transfer surface in small volumes of the chamber;
(b) Forced circulation of the moderator in a single-phase state. Such a method with the use of supercritical hydrogen at 1.5 MPa and 30–50 K has been implemented in a number of reactors and accelerators; e.g., Risø – Denmark [43]; BER-II – Germany [58], ISIS – UK HFIR (Annex III)– USA [62, 63], (Figure 16), This demands use of hydrogen pumps at low temperatures. The thickness of the Al chamber increases to 6–8 mm for operation at 1.5 MPa instead of 1.5–2 mm at the pressure of 0.15–0.4 MPa, which results in increased heat liberation in the material. A description of the supercritical CNS built at HFIR, Oak Ridge, USA is given in Ref. [160];

(c) By means of natural condensation of vapour of a boiling moderator in the condenser of a vertical thermosyphon. This is the simplest system in which the supply and discharge pipes are arranged vertically to the source chamber and the condenser. The liquid moderator flows down one pipe to the source chamber, and the vapour is discharged into the condenser through another pipe, where it is condensed and flows back to the chamber due to gravity. This method was first used at a high-flux reactor in ILL, France [42] 49]. Heat removal by using this method can be carried out up to 250 kW. However, at low heat loads of about 500 W, unstable operation may occur due to the appearance of bubbles in the down-take pipe and a change in the direction of flow. This method does not allow the moderator to cool below the boiling point;
(d) A more complicated situation connected with heat removal appears when using natural circulation with a boiling moderator that has a horizontal configuration of supply and discharge pipes to the CNS chamber. Such systems worked with CNSs at the reactors DIDO [30, 31], EL3-Saclay [32, 33], FRJ-Jülich [39]47], etc., but with a total thermal load of 0.1–1 kW. Placing sources with such systems in more severe radiation conditions will lead to significant heat removal problems;
(e) The CNSs at OPAL (Australia) [71, 72] and CARR (China) [73, 74] employ a vertical, natural circulation thermosiphon (Figure 16) and operate with a liquid deuterium moderator, which has a higher moderator density than boiling types. Helium coolant is split into two flow paths and circulated through the heat exchanger as well as around the double-walled moderator chamber. The moderator chamber flow enables a so-called 'stand-by' mode where the reactor is able to run at full power even when the CNS is not operational at cryogenic temperature, fully utilizing the other functionalities and services of the multi-purpose reactor.

4.5. ENGINEERING DESIGN

Good examples of basic literature on the engineering design are given in Refs [5] and [17], and technical design reports for spallation sources in Refs [161–165].

The engineering implementation of the CNS design concepts needs to consider all interfaces with all the reactor or accelerator systems. A cold moderator is one part of a CNS system, which can be composed of the following parts: (i) Moderator system (moderator chamber and buffer tanks); (ii) Vacuum system; (iii) Thermal and/or pre-moderator; (iv) Neutron reflector (e.g., Be, D_2O); (v) Cryogenic cooling system; (vi) Gas blanketing system; (vii) Pipework; (viii) Shielding; (ix) Instrumentation control and safety system. References [166]–[170] are useful sources for further information on structural materials for CNSs.

4.5.1. High level requirements

Engineering design needs to deliver a CNS that will fulfil the basic functional, operational, and safety requirements:

(a) Requirements for cold moderators are: (i) Deliver the desired key performance indicator (Section 3.2); (ii) Structural support and position of the moderator; (iii) To enable handling of active components; (iv) Cooling the radiation heat in liquids and solid metal bodies;
(b) Safety requirements are: (i) Nuclear safety – detachment from reactor or accelerator safety case; (ii) Radiation safety – shielding and avoidance of streaming; (iii) Non-radiation-related safety – hydrogen blanketing and confinement;
(c) Regulatory requirements include: (i) Compliance with facility license conditions; (ii) Compliance with industrial standards.

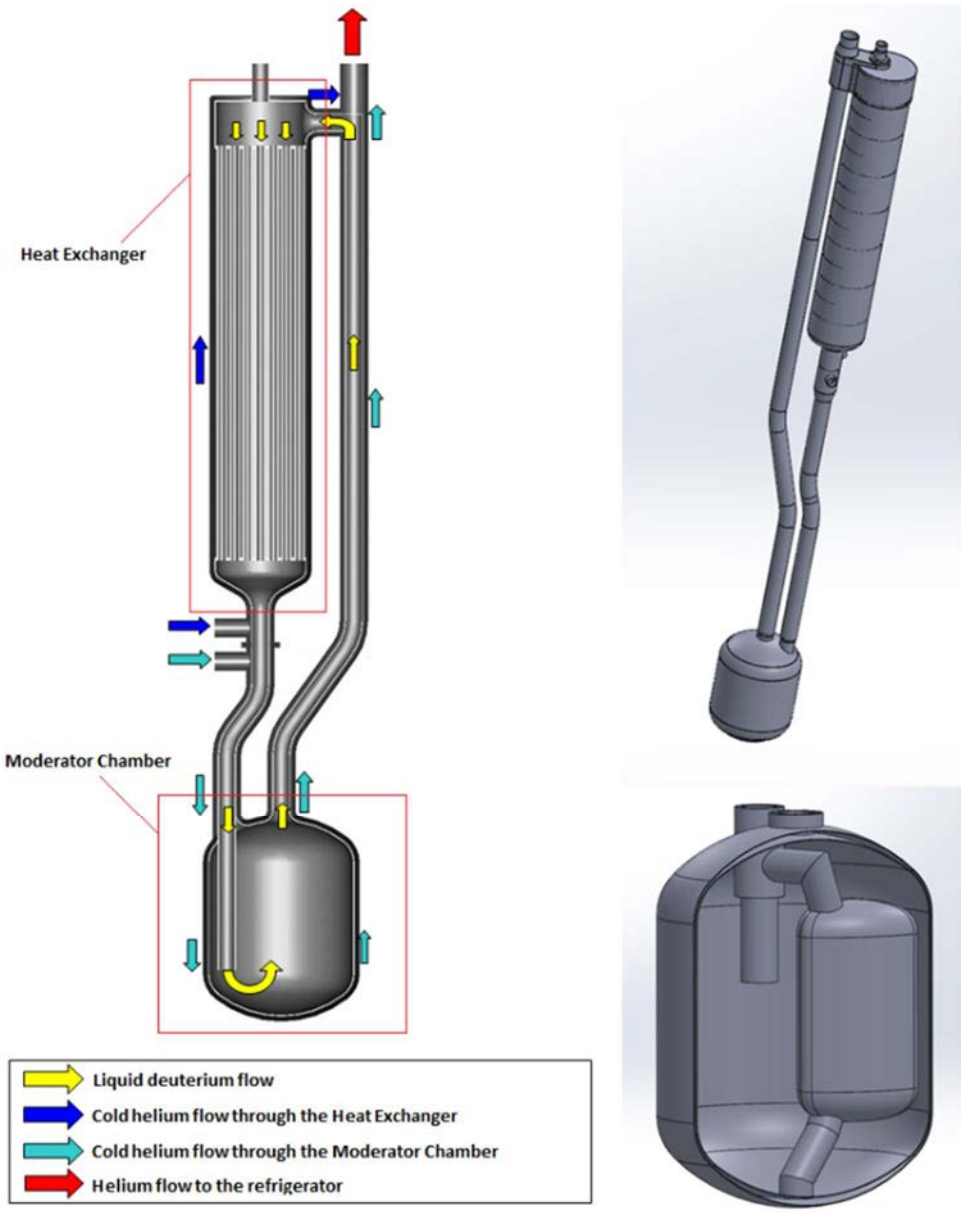

FIG. 16. The layout of cooling of a vertical full liquid thermosiphon with a double-walled moderator chamber (courtesy of W. Lu, ANSTO).

4.5.2. Functional specifications of sub-systems

The following considerations are to be made in the full specifications of the CNS: (i) Adequate heat removal from the moderator under all anticipated operational conditions; (ii) Achieve the required *o*-/*p*- ratio if hydrogen is used; (iii) Sound material choices for vessels, structures, pipework, etc.; (iv) Choice of a reflector (for example Be or D_2O); (v) Quality assurance on manufacturing, testing, and installation; (vi) Commercial accessibility of materials and instruments; (vii) Weight limitations; (viii) Pressure ratings of all relevant vessels, pipelines, and instruments; (ix) Temperature range of all relevant vessels, pipelines, and instruments.

4.5.3. Fluid data for engineering calculations

The fluid data for hydrogen are highly dependent on the temperature that has to be considered in the calculation. In particular, the heat capacity goes down significantly at low temperatures, resulting in fast increases in temperature. Hydrogen is ~30 times (depending on *P*, *T*) more

compressible than water, which is considered incompressible. Air, which is considered as compressible, is ~300 times more compressible than hydrogen. Therefore, hydrogen can mostly be assumed to be incompressible. However, treating hydrogen as truly incompressible would lead to higher pressure peaks if pulsed heat inputs were considered, which would result in more conservative calculations. On the other hand, overestimation of the pressure pulses will increase the costs for the hydrogen loop and safety devices, as well as limit the design possibilities for the CNS. Therefore, one needs to consider whether the higher simulation effort by using *T*- and *P*-dependent fluid data would be justified or not.

4.5.4. Materials under neutron irradiation

The evaluation of radiation-induced lifetime is a rather complex matter that depends on the amount, type, and energy spectrum of the radiation, the environmental conditions, and the irradiated material itself. Material subject to irradiation undergoes a variety of damage processes and evolution of its microstructure that affect its physical properties. These include:

- Transmutation of alloy components, which may be dominated by the thermal (or cold) fraction of the neutron flux, where neutron capture cross sections are highest (e.g., ingrowth of Si in Al; see Figure 17);
- Fast neutron transmutation, which may ultimately generate hydrogen and He gas bubbles from protons and α particles produced via (n,p) and (n,α) reactions, respectively; e.g., in steels $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$ and $^{59}Ni(n,p)^{59}Co$;
- Neutron displacement damage, which is another major form of material degradation where the energy of the neutron exceeds the threshold (typically ca. 20–90 eV) for displacement of an atom from its equilibrium site [171], leading to the creation of Frenkel pairs of vacancies and interstitials that may either recombine or diffuse and lead to changes in the microstructure (e.g., production of dislocations, dislocation loops, voids, etc.) and related loss of mechanical strength and changes in dimension (e.g., swelling, elongation).

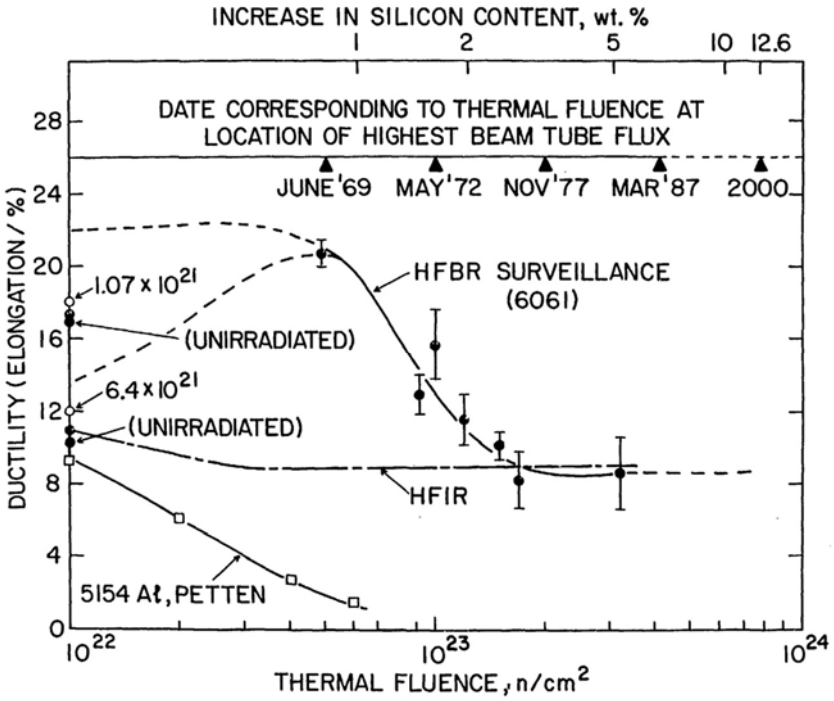

FIG. 17. The effect of thermal neutron radiation on silicon content of Al-6061 in the HFIR and HFBR reactors. Reproduced from Ref. [169]. U.S. Government Work.

Material lifetime for a specific material is often quoted in terms of displacements per atom ('dpa'), which can be calculated based on neutron fluence. However, dpa is a measure of dose (energy deposition) rather than a direct measure of material damage and can overpredict damage due to the presence of various temperature dependent recovery mechanisms. More modern concepts such as athermal recombination corrected-dpa ('arc-dpa') and replacements per atom ('rpa') have been shown to be more suitable to make predictions of microstructure change and damage [172–173].

A cold moderator for a spallation source could be exposed to a high fast neutron flux, so that a more stringent lifetime criterion is needed. Two other factors may need to be considered when using material data from one study for another application: (i) dose rate and (ii) whether the radiation is continuous or pulsed; e.g., pulsed radiation produces new primary defects only when the beam is on, whereas their diffusion, recombination, and recovery continue when it is off.

Regarding processes involving degradation of hydrocarbon moderator materials, see Sections 2.2.2, 11.1, and Annex I.

4.5.5. Materials for moderator chambers

Structural materials of the source have to have the following properties:

- Minimum absorption cross section;
- Having a high and stable coefficient of heat conduction;
- High strength at low temperatures;
- Resistance to brittle fracture at cryogenic temperatures;
- Weldability and ductility when manufactured;
- Resistance to radiation;
- Ensuring product life of at least 10 years.

Aluminium alloys have a face-centred cubic lattice and are proven materials that have been extensively used to produce moderator chambers. Aluminium is almost transparent for cold and thermal neutrons and is, therefore, typically used as a moderator vessel material. However, the strength of pure Al is much too low to keep the stress from internal pressure within the allowable range. Heat treatable Al alloys (Al–Mg–Si, 6000 series) and non-heat treatable (Al–Mg, 5000 series) have been used. Typically, these alloys do not have brittle fracture temperatures and therefore retain ductility and viscosity at cryogenic temperatures. Mechanical properties of Al alloys AMg3 and AMg5 as a function of temperature are shown in Table 4 and for 6061 are given in the literature [174]. The heat treatable Al alloys Al 6061-T6 is used in many facilities like SNS, ESS, and J-PARC. The basic material strength is the highest of the potentially usable alloys. However, the high strength values based on the heat treatment process (T6) is lost when re-heated above ~130 °C. Figure 19 illustrates this fact. The performance of Al 6061 produced via ultrasonic additive manufacturing under neutron irradiation has recently been examined [175].

Under irradiation to a neutron fluence of 1.2×10^{21} cm^{-2}, the ductility of Al alloys decreases slightly and remains high enough thus ensuring long service lifetime of the source (Figure 18). Aluminium alloys AMg3, AMg5, SAV-1, AD33, 5052, and 6061 can also be considered as the structural material of the source chambers, as they have the good properties that can meet the operational requirements.

TABLE 4. MECHANICAL PROPERTIES OF ALUMINUM ALLOYS AMg3 AND AMg5 AT CRYOGENIC TEMPERATURES [176]

Alloy	Preform, treatment temperature	T K	σ_B MPa	σ_{02} MPa	δ %
AMg3	Sheet - 2 mm,	293	201	100	25.3
	Annealing at 350–420 °C	77	313	104	48.4
		20	458	126	41.3
		4.2	451		36.7
AMg5	Sheet - 2 mm,	293	300	130	23
	Annealing at 350–420 °C	90	390	150	40
		77	420	160	44
		20	520	170	33

Note: δ is the relative elongation;
σ_B is the tensile strength;
σ_{02} the yield strength.

In principle, all moderator vessels have to be welded. Depending on the number of welds, the distance to each other and the welding type itself, e.g., Tungsten Inert Gas (TIG), laser, electron beam, the whole vessel can lose the extra strength given from a heat treated alloy; e.g., TIG welding demands pre-heating of the vessel, so that the T6 condition is lost globally. This can be avoided by using electron beam welding. Nevertheless, reduced strength has to be expected in an area around the weld (Figure 19). However, by putting the welds in a low stress area (if possible), some benefit can be retained from the T6 treatment. On the other hand, e-beam welding demands a very high manufacturing tolerance (‘zero gap’).

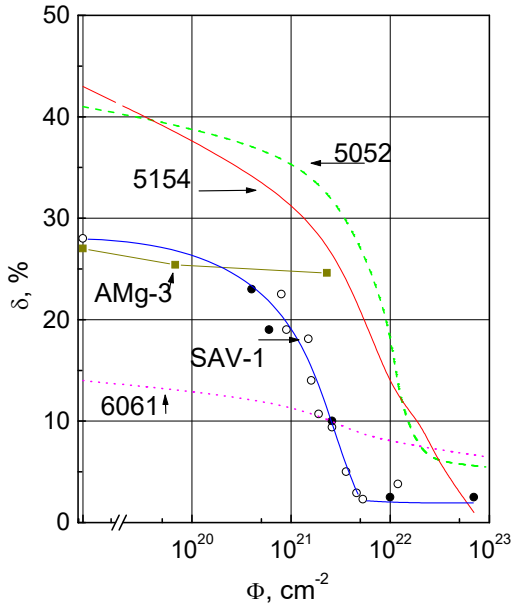

FIG. 18. Dependence of relative elongation (δ) on fast neutron fluence(ϕ) (E > 0.1 MeV) for various Al alloys. Sources: 6061, 5154 and 5152 [177], SAV-1 [178–179] and AMG3 [177].

Another issue when using Al 6061-T6 is the need for a welding filler to avoid heat crack formation, which is encouraged by the alloy composition, particularly by the Si and Mg content. Therefore, the filler needs to have a relatively high Si content for example, which can be satisfied, e.g., by Al 4047 with 12% Si. Non-heat treatable Al alloys don’t need a filler. If a decision is made to use Al 6061-T6 and the intent is to benefit from the T6 treatment, it is necessary to consider the higher manufacturing effort and costs, possibility of warping during manufacturing, risk of heat cracks, more complicated filler geometry, and the high tolerances.

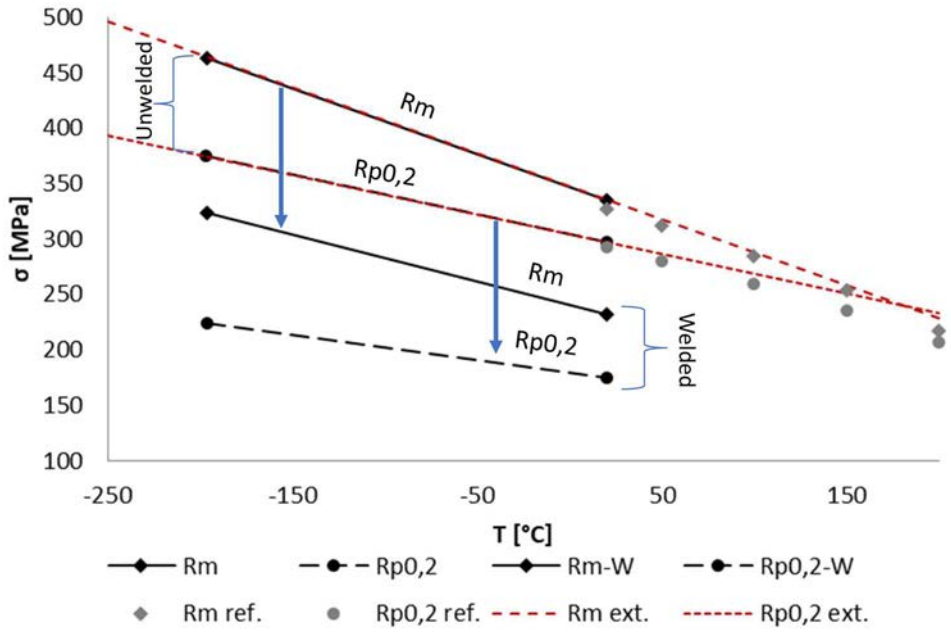

FIG. 19. Low temperature yield and tensile strengths of welded and unwelded Al 6061-T6. The measured tensile strength (Rp0,2) and yield strength (Rm) at liquid-nitrogen temperature and room temperature (black dots) are listed as unwelded and welded (-W). In addition, data above room temperature has been added from the RCC-MRx code ('ref.', grey dots) and the extrapolations ('ext.', broken red lines) [153]. The shown welded values are very close to those of 5000 series Al.

As can be seen in Figure 17, with increase of thermal neutron fluence the ductility of Al decreases. This is primarily due to Si transmutation arising from the capture of a thermal neutron by ^{27}Al and subsequent β decay to ^{28}Si. Whereas the ductility for 5000 series Al disappears completely, the ductility saturates for 6000 series Al at about 8%. With this remaining ductility, 6000 series Al alloys have the potential for longer lifetime under irradiation than 5000 series. Unfortunately, in the literature there is practically no information about the properties of structural materials under the combined influence of radiation and low temperatures. Nevertheless, many years of experience in the operation of sources at various reactors show high reliability of sources using Al alloys as structural materials.

Zirconium alloys are widely used for the manufacture of nuclear reactor elements. Like Al alloys, they possess good 'transparency' for neutrons, but Zr alloys have higher mechanical strength properties than Al alloys. A CNS made of the Zr-alloys Zr–1% Nb and Zr–2.5% Nb was successfully operated at the WWR-M reactor (channel V-13, PNPI, Russian Federation) for several years. There are quite a lot of experimental data on the strength properties of Zr alloys at various high irradiation temperatures (50–350 °C and above) and neutron fluences (10^{19} to 9×10^{22} cm^{-2}). Zirconium alloys can also be used reliably to create vacuum containers (CNS shells). The use of Zr-alloys for CNS chambers as construction materials can be justified; however, the design and manufacture of the chamber has to be carried out more cautiously, with additional studies and justifications both of the initial material and welded junctions.

4.5.6. Pipework (invar and stainless steel)

Due to the low temperature of the moderator fluid inside the pipework and the fact that compensators ought not to be used (due to embrittlement by irradiation) an alternative material becomes necessary. In contrast to the other materials, Invar has almost constant low thermal expansion over the full temperature range of interest and is therefore a typical material for low

temperature applications (Figure 20). For this reason, Invar can be used between an Al vessel containing the cold moderator and the stainless-steel cryo-coupling. However, by using Invar, the material transitions have to be handled. The suitability of the connections (Al–Invar and Invar–stainless steel), typically friction welded joints, need to be verified by experiments, including thermal cycles and burst tests, because such a connection is not covered by design codes like RCC-MRx [170]. Additionally, even a relatively small exposure of radiation leads to an increase of the thermal expansion coefficient of Invar. To benefit from the very low thermal expansion of Invar, it is recommended, to place Invar pipework in an area that will receive less than 0.001 dpa.

4.5.7. Stainless steel structural material

The cobalt impurities in steel can be of particular interest due to activation. Under irradiation ^{60}Co is produced, whose presence is the main driving factor for waste handling in the medium term. For example, the RCC-MRx code [170] defines purity classes for maximum allowable cobalt content with limits of 0.25%, 0.05%, and 0.01%. There is a trade-off between purchasing low-Co steel, which is difficult to get because of availability and, therefore, often more expensive versus the handling and storage of less active components at a later state.

For water-cooled, stainless-steel parts close to the CNS vessel, corrosion resistance is a design concern. High radiation levels accelerate the corrosion rate. Depending on the expected irradiation over the lifetime of the components, a cost comparison ought to be done to decide whether to use high corrosion resistance stainless steel, e.g., SS316L, or less corrosion resistant stainless steel, e.g., SS304L, which is a lower cost alternative.

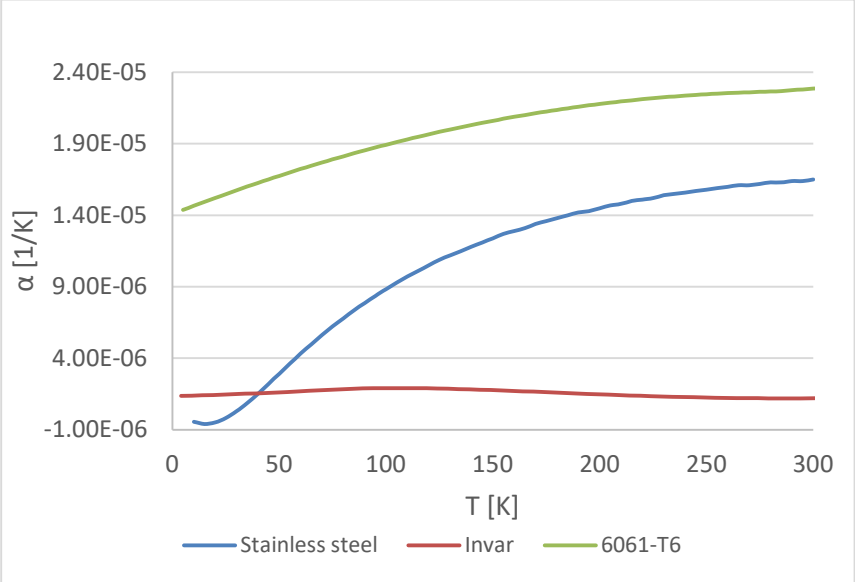

FIG. 20. Thermal expansion of stainless steel, Invar 36, and Al6061-T6 as a function of temperature. Data are taken from Ref. [180].

The low thermal conductivity of stainless steel is challenging for the cooling design. The thermal conductivity of stainless steel at 20 °C is 14.28 $W \cdot m^{-1} \cdot K^{-1}$, which is about four times less than carbon steel and twelve times less than Al. The cooling design for those stainless steel parts close to the source that receive high heat deposition may demand a volume ratio of cooling water to stainless steel approaching 1:1.

The question as to whether the pulsed nature of neutron irradiation (see Section 4.5.4) was important for structural steels near the target of the ESS was examined. Reference [181] concluded this was not important for their application.

4.5.8. Beryllium reflector

In a cold moderator system, a Be reflector may be used to increase the neutronic performance. Beryllium is a neutron multiplier, via (n, 2n) reactions, and a reflector. Although Be is a metal, it is not a structural material, but can be surrounded by an Al vessel. As the Be needs to be placed close to the source, cooling, typically light or heavy water, is needed.

To increase neutronic performance, Be with a purity of greater than 95% is needed. But most important is the nature of the impurities, since certain impurities can, even at a low level, impact the performance of the moderator if they possess large absorption cross sections. Furthermore, the smaller the number of impurities that activate strongly, the easier it is to handle a Be reflector when it is exchanged and disposed of. The other property influencing the neutronic performance is the grain size: the Be ought to be isotropic with grain size of ≤ 20 μm.

Not relevant for the neutronic performance but for quality control of the Be, are surface defects of this brittle material. A typical specification could be "A penetrant inspection of all parts has to be performed. The following acceptance criteria has to be met: (i) Cracks are not permissible; (ii) Pores cannot exceed 1.25 mm diameter; (iii) There cannot be in excess of 3 pores per square inch."

4.6. LIFETIME DEGRADATION OF STUCTURAL MATERIALS

The main degradation effects to consider during evaluation of the recommended operational lifetime of a CNS are:

(a) Effects of radiation (swelling, hardening, elongation decrease, fracture toughness);
(b) Cyclic loading;
(c) Fatigue crack propagation;
(d) Corrosion.

The lifetime of a CNS is dependent on fatigue and radiation damage. Corrosion and/or erosion do not normally limit the lifetime. Fatigue needs to be analysed taking shutdowns, beam trips, pulsed operation, and all relevant load variations into consideration. However, material data for irradiated structural material at cryogenic temperatures is very limited.

The life limiting critical element of the CNS is the Al vessel containing the moderator substance. In summary, the mechanical properties of the AlMg and AlMgSi alloys are affected by three radiation induced ageing mechanisms:

- Al→Si transmutation caused by thermal neutron transmutation: $^{27}Al(n,\gamma)^{28}Al(\beta^-)^{28}Si$;
- Gas production (H_2, He) and swelling caused mostly by fast neutron transmutation;
- Matrix defects (dislocations, voids) induced by epithermal and fast neutrons.

The irradiation effects depend on the fluence, irradiation temperature, and the neutron spectra (the ratio of fast/thermal neutrons). The neutron fluence accumulates over time. The maximum value given in the RCC-MRx code [170] (A3.2A.32) for negligible thermal neutron fluence is 1.8×10^{22} cm^{-2} at 20 °C. For fluences exceeding this value, rules for radiation damage have to be applied. According to the RCC-MRx code, a maximum thermal neutron irradiation of

6.7×10^{23} cm^{-2} is allowed. However, the design code focuses on material degradation due to embrittlement caused by Si transmutation, due to thermal neutrons.

Fast neutron irradiation induces a high radiation damage rate due to the displacement of atoms. For reference, the operating experience at HFIR reactor, Oak Ridge National Laboratory shows that Al alloy Al 6061-T6 is able to withstand up to 40 dpa. Nevertheless, self-annealing of displacements and point defects in the Al at elevated temperature, ought to be considered, which may permit relaxation of the dpa-based lifetime limit (see Section 4.5.4).

4.7. UNCERTAINTIES OF DESIGN ASSUMPTIONS

The engineering design phase is always based on a neutronic simulation. Underestimations, and design simplifications in this simulation will influence the engineering design significantly. It is therefore important to bear in mind the great influence of the neutronic simulation and to estimate its associated uncertainties before starting the engineering design process.

For accelerator-based neutron sources, the nominal proton beam parameters may vary during operation. Long and short beam trips can occur, which can lead to fatigue issues. The beam can move for a short time closer to the moderator, temporarily raising the heat load. To be on the safe side, these abnormal events have to be analysed and considered in the calculations and documented in the load history report.

The fluid dynamic analysis will deliver P and T values for the structure's mechanical simulation. The simulation is just an approximation of the real behaviour. Therefore, the estimation of its associated uncertainty is a fundamental part of the analysis. There are model uncertainties (design simplifications), uncertainties in the estimation of the load (pulse and pulse shape), uncertainties in the material data (temperature and pressure dependency), and simulation uncertainties (meshing and time stepping) for example. Those groups of uncertainties need to be quantified.

For an accurate structural mechanical simulation, one needs to consider the influence of irradiation (change of heat conductivity of Al for example), possible fatigue by pulsed heat or beam trips, the reduction of wall thickness by corrosion, creep, and buckling. Additionally, the definition of a welding reduction factor as a function of accessibility, method, type, and the definition of a safety factor for the tensile strength or yield strength based on the individual design guideline is needed.

5. MANUFACTURING AND TESTING

A quality and safety assurance system needs to be implemented and maintained during the design process, e.g., according to ISO 9001[15].

5.1. QUALITY ASSURANCE

The following sections outline some of the major components of quality assurance (QA) for a CNS project.

5.1.1. Quality management

Before starting the manufacturing phase, the usual practice is to perform a critical design review with an independent committee who look over the proposed design solution. The considerations given for technical requirements in the bidding process for a research reactor detailed in the IAEA report [182] may be useful to review as many considerations would be in common. During manufacturing, independent quality control is done either by an internal independent quality department, and/or by an external independent body. For analysis, an accredited laboratory is needed. After completing manufacturing, standard practice is to perform a factory acceptance test (FAT) before the shipping and installation can begin. Finally, a site acceptance test (SAT) is performed prior to entry into service. Appendix I contains an outline of a typical quality assurance document package.

5.1.2. Inspection plan

Inspection needs to be done during manufacturing according to the design code being followed and classification. For a pressurized hydrogen cold moderator, an independent inspection body is generally involved. Before the start of manufacturing, an inspection plan is drafted and agreed with the quality department and an independent inspection body. Appendix II contains a outline of a typical quality assurance inspection plan.

5.1.3. Release of drawings

The manufacturer has to complete the working tasks based on the final approved manufacture drawings. All requirements described in the final drawings have to be strictly observed:

(a) Dimensions and tolerances;
(b) Machining treatment conditions;
(c) Thermal treatment conditions;
(d) Requirements for welding;
(e) Requirements for welds testing;
(f) Requirements for surface finishes and other special requirements;
(g) Required tests and conditions.

Preliminary agreed local standard requirements for production can be used. The contractor's technical and QA managers are responsible for the correct status of the supplied drawings stamped 'For Manufacture'. Codification has to be developed for control for documentation traceability as well as providing a means for part identification and control. The manufacturer has to carry out all inspections in accordance with the respective specifications, inspection and test plans, procedures, and standards, observing all specified witness and hold points.

[15] https://www.iso.org/iso-9001-quality-management.html

5.1.4. Release of technical documentation

The manufacturer has to produce technical documentation for production. The documentation has to correspond to the requirements of the detailed engineering design phase and drawings. The technical documentation is produced for each component and for assemblies including:

- Process charts;
- Process charts for welding;
- Quality control (QC) documentation.

The technical manager and QA manager are responsible for the correct status of the manufacturing documentation. Prior to starting the work, all technical documentation has to be agreed between the manufacturers and the technical and QA managers.

5.1.5. Feedback flow chart

Any feedback needs to take into account that:

- Any changes arising during the production phase and affecting original drawings and/or specifications have to be approved by the technical manager and QA manager;
- Any significant change in the product design, fabrication methods, materials, and/or manufacturing processing have to immediately be notified in an Engineering Deviation Report. Significant changes are those that may affect the form, fit, function, dependability, safety, or interchangeability of any item and/or impact, directly or indirectly, on other interfacing components. The feedback flow is shown in Figure 21.

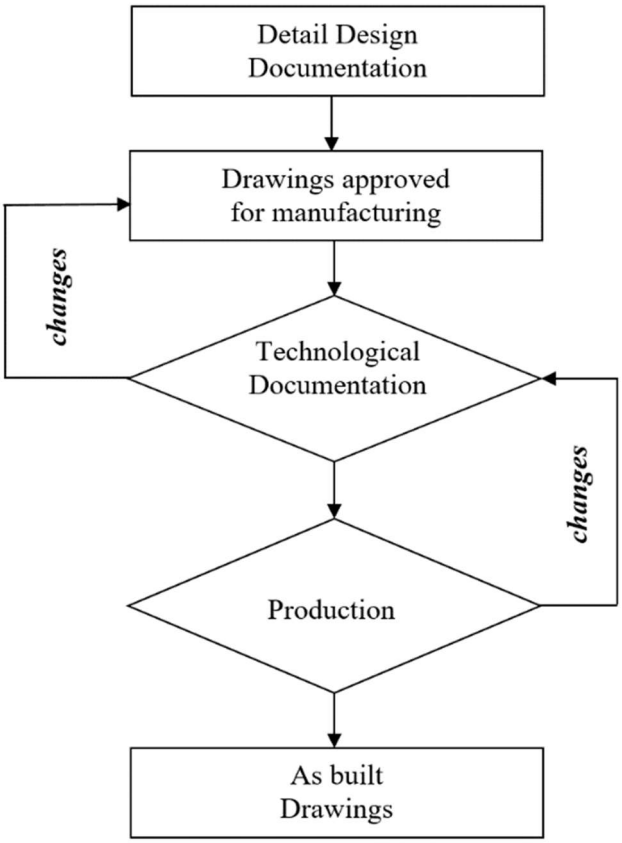

FIG. 21. Feedback flow chart.

5.1.6. Final documentation

For final documentation of work and procedures the manufacturer has to maintain records to ensure that all fabricated items (including spare parts, testing components) are of the proper configuration, and that all approved changes are incorporated into the as-built drawings and final documentation. The technical manager of the contractor is responsible for processing all deviations regarding the originally released detailed design drawings into the as-built drawings. The documents associated with the final manufactured state of the CNS are described further in Section 8.6.

5.2. PROCUREMENT OF MATERIALS

For the procurement of materials, the material selection has to be made during the design phase according to the materials definition and the acceptance criteria for the strength and lifetime requirements. A 'Materials Reception and Inspection Plan' has to be issued and further approved by the appointed person in charge of quality management. All the materials and consumables for manufacture have to be supplied with valid certificates, and batches have to have appropriate visible identificatory marks. Reception control of incoming materials includes dimensional verification and visual inspection of the surface. Storage conditions of materials and products and traceability of the manufacturing process have to be assigned.

For all commercial items (e.g., nuts, bolts, washers, O-rings, fittings, etc.) conformity certificates, indicating compliance with standards, specifications and delivery order have to be provided.

Composition and mechanical properties of raw materials have to conform to the corresponding standard for those materials. If material properties and parameters satisfy the applicable standards and specifications, the material can be used for production. The manufacturer is fully responsible for using a proper batch for production. All billets for production ought to have a particular mark on the surface for identification of the material batch. This mark is indicated in the technical documentation for the component.

Composition and mechanical tests will be carried out for batches during production of components according to the approved 'Inspection and Tests Plan' (ITP). The manufacturer has to guarantee that the samples provided for tests are taken from the same batch as that to be used for production. A final result of incoming materials control has to include material certificates, mechanical properties test reports, and composition test reports, as required by the ITP.

5.3. MACHINING

The machining is produced according to approved technical documentations and a production plan. A process chart includes 100% dimensional control procedures to satisfy the specifications of the component. A QC document for machining contains critical dimensions for details and assemblies that have to be examined after manufacturing. Critical dimensions are those that may affect the form, fit, function, dependability, safety, or inter-changeability. Results of measurements are recorded in an associated report. Instruments for measurement have to be tested and calibrated. After the quality check, the worker and manufacturer's quality inspector have to sign the QC document.

5.4. WELDING

Welding is made according to the approved technical documentation for welding and the production plan. The technical documentation for welding includes requirements for examination of welds based on the applied code, according to the quality level of the element. Quality control examination can include radiographic, liquid penetration, and ultrasonic tests, etc. The acceptable limit for imperfections is determined by the applied code. Acceptable limits for leaks are determined by project requirements.

After welding, an examination of the welds by an appropriate method has to be done. Welding examinations have to be recorded in an appropriate QC welding report defined by the QA program. Welding relevant test reports have to cover:

- Welding procedure specifications and procedure qualification records with relevant reports;
- Weld filler material certificates;
- Heat treatment report (if acceptable);
- Welder qualification report with relevant test reports;
- Visual, dimensional, and dye penetration inspection report;
- Leak and/or hydrostatic test records;
- All records have to use identification of weld maps. Records have to contain weld ID, date of weld, welding procedure specifications, welder ID filler material batch, material heat number, sign off, visual, and dye penetration report numbers.

5.5. TECHNICAL SAMPLES

Before starting element/component production, the manufacturer has to fabricate samples of the elements/components to demonstrate the correctness of the process followed. The list of samples and tests to be carried out have to be defined by contractor in the detailed engineering stage and agreed with the manufacturer. The elements that require production samples are identified from the point of view of their required quality level, safety level, difficulty for production, presence of welding, etc.

The sample can be a copy of the element or of the most critical part of the element. The fabricated sample is exposed to suitable tests and measurements, like a pressure test, radiographic examination, leak test, weight measurement, dimensions, and shape measurements, etc. Production of critical elements can begin only after steady positive results are obtained from the sample tests. The number of required samples for each element will depend on the examination and analysis of results obtained from the samples.

5.6. TEST OF MANUFACTURING

The entire manufacturing process is controlled by verification tests defined in the ITP. The manufacturing phase will include also tests for intermediate assemblies to prove they meet the specification requirements in the final assembly. The assemblies' testing will depend on the specification requirements of the ITP: leak test, overpressure strength test, pressure-cycling test, and/or thermal-cycling test, etc. Test results will be recorded in a report. The report has to contain the following data:

- Data on the examined assembly;
- Purpose of the examination and the examination method;

- Piping and instrumentation diagram of the test;
- Description of measurement instruments, certificates, and calibration;
- Name of the operator and level of his/her certificate of competence;
- Examination plan;
- Result of the test;
- Date of the test.

5.7. ACTIVATION, ACCESSIBILITY, MAINTAINENCE AND REMOTE HANDLING

Cold neutron sources become activated over time and the expected doses that may be received by staff during access for inspection, upgrade, service, or decommissioning, have to be calculated during the design. Radiation levels for any component at any time in its lifetime depend on neutron fluence, exposure time, cool down time, and material. The levels and compositions of material impurities are of particular importance, e.g., Co content in steel, or U in Be. Depending on the dose levels encountered, direct hands-on handling, handling with long tools, remote handling, or remote handling with a cask are possibilities. It ought to be possible to divide larger components into sub-components of size that are reasonable to handle at the installed site. Connection points need to be added into the design to enable handling of the active parts. The requirements for remote handling need to be considered at the very beginning of the design. A connected hot cell with tooling is another facility that could be considered if high fields are expected.

In a value engineering approach, an evaluation of which components of the CNS to keep, repair, or replace throughout its design lifetime is made. Various scenarios have to be thought through and questions asked during design. For example, does preventive or corrective (due to failure) maintenance need to be done during the lifetime of the CNS? (Often replacement proves to be the most cost-effective alternative.) What consequences would a failure of any one component have for further operation of the CNS and the rest of the facility?

6. SAFETY ANALYSIS AND LICENSING

As the safety requirements and regulatory framework may vary significantly from country to country, this section will only concentrate on the technical aspects of the CNS safety case. The safety of the CNS normally has three primary areas of concern:

(a) Nuclear safety (for reactors);
(b) Radiation safety;
(c) Non-radiation-related safety (especially hydrogen safety).

Licensing is especially relevant for reactor-based CNS. It may be dealt with as part of the reactor operation licence because the CNS is an integral part of the reactor. Therefore, a safety classification of structures, systems and components (SSCs) needs to be conducted according to the national regulatory framework. Safety classification ought to be based on the safety analysis report where consequences of severity are identified. Safety requirements are relevant to the classification.

By following IAEA Safety Standard Guides SSG-20 [183], SSG-22 [184], and SSG-24 [185], the safety analysis report documents all relevant postulated initiating events in the CNS based on identification of hazards, and how the safety design provides adequate protection in such events. Some postulated initiating events are unique to the CNS due to its complicated cryogenic process, where rapid temperature change can cause strong pressure transients and thermal stress in structural materials. Leak tightness and redundant containment to prevent tritium leakage is crucial for hydrogen (or deuterium) moderators. Therefore, the CNS has special needs for its own protection, which, depending on design, may even trigger reactor shutdown. The distinction between those protective actions that are related to nuclear safety (e.g., to prevent damage to the reactor core) and those that are related to the CNS (e.g., to prevent damage to the moderator chamber) need to be clearly documented in the safety analysis report.

Safety design of the CNS can be achieved by conforming to international and national standards (e.g., the KTA[16] German nuclear standard, the RCC-MRx[17] French nuclear standard [170], the ASME[18] American standard, the ATEX 114, 2014/34/EU European directive[19]), appropriate for the safety classification, as for the rest of the reactor.

6.1. NUCLEAR SAFETY

Nuclear safety includes not only the fulfilment of safety functions for the reactor core, but also the ability of SSCs to perform their intended safety function in the whole reactor plant.

Among the ‘postulated initiating events’ for a CNS, two types of events are nuclear safety related and thus warrant special attention, namely:

(a) Reactivity transient: This is caused by the phase change of the moderator (e.g., evaporation and liquification of hydrogen). The transient can be simulated by reactor kinetics codes. While the cross-section library of common moderators such as liquid hydrogen, liquid deuterium, or liquid methane is readily accessible, those of more exotic molecules such as

[16] The Nuclear Safety Standards Commission (Kerntechnischer Ausschuss - KTA) https://www.kta-gs.de/welcome_engl.htm
[17] AFCEN RRC-MRx, https://www.afcen.com/en/106-rcc-mrx
[18] ASME codes, https://www.asme.org/wwwasmeorg/media/resourcefiles/shop/standards/new%20releases/nuclear-resources-brochure.pdf
[19] ATEX 114, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0034&from=de.

mesitylene may require in-house computation or acquisition through third parties. Reactivity transients caused by the CNS may be considered within the context of general reactivity insertion events of the reactor in the safety analysis report. Reactor shutdown margins also need to take the CNS reactivity into account. Some nucleonic power channels may be at locations shadowed by the CNS moderator. As a result, phase change of the moderator can interfere with reactor control, if readings of those power channels are affected during the reactivity transient;

(b) Pressure transient: This can be caused by rapid temperature change resulting in sudden evaporation of the moderator, or in a more extreme hypothetical scenario by chemical reaction between hydrogen and oxygen (as described in Section 6.3). High pressure peak can challenge the structural integrity of the CNS, and even the reactor core and other associated SSCs if not contained.

The risk to reactor control imposed by reactivity transient is self-evident, while pressure transients have the potential to physically challenge the structural integrity of the reactor core and other associated SSCs.

Another postulated initiating event of interest from the CNS is the spill of cryogenic liquid during a catastrophic failure of the moderator chamber. Safety analysis needs to demonstrate that such an event, although highly unlikely, can be fully contained and does not cause unacceptable damage to any reactor SSCs important to nuclear safety. A list of the major safety points covered in the CNS that was installed at the BER-II reactor, Berlin, Germany is given in Ref. [101].

6.2. RADIATION SAFETY

The requirement to assure radiation safety of the CNS, from design to operation and eventually to decommissioning, is the same for a reactor or accelerator facility, in general. However, there are some special considerations affecting CNSs that need to be considered:

- Activated gas impurities can remain condensed at cryogenic temperatures during operation for a long time and be released when the CNS warms up;
- Due to the design lifetime under neutron irradiation, the CNS may require replacement or upgrade on a regular basis (e.g., every ten years). Minimising radiological impact during upgrades needs to be considered in the material choice and piping connection provisions during the original design (see discussion in Section 5.7).

In addition, if deuterium is used as the moderator, the build-up of tritium in the deuterium inventory over many years of operation may be much more significant than that in a hydrogen CNS. As a low energy β emitter, tritium has low radiological impact when contained. Nevertheless, its ability to readily replace hydrogen in light water molecules and to become an airborne activity, which readily enters the human body, makes tritium handling an important radiological safety challenge. Accordingly, considerations for the management and eventual disposal of the deuterium inventory need to take tritium build-up into account (see Appendix III for more details).

6.3. HYDROGEN SAFETY

During normal operation of hydrogen CNS, the hydrogen pressure is kept constant at about 150 kPa or so, which corresponds to a temperature of 25 K in the moderator shell and loop. The use of hydrogen, a highly explosive and flammable gas, in significant quantity introduces a serious fire risk. However, this risk can be adequately managed if the right design and

operation/maintenance practice is adopted. Guidance for hydrogen safety is available, (see for example ANSI/AIAA G-095-2004[20], Guide to Safety of Hydrogen and Hydrogen Systems [186]). The safety requirements regarding explosion for a deuterium CNS may be higher than those for a hydrogen CNS, because the volume of the deuterium moderator used is much larger. For those CNSs employing solid moderators such as hydrocarbons, due to the radiolysis (see Sections 2.2.2 and 11.1, Annex I) hydrogen safety needs to be considered as well, although to a lesser extent.

Where a potentially explosive moderator material like hydrogen is introduced in a reactor building, a provision has to be established to ensure that the items important to safety of the research reactor are protected by means of a barrier or other physical arrangement from an unexpected explosion of the moderator. To eliminate any explosive risk that may affect nuclear safety, containment of the relevant parts of the CNS needs to be designed to withstand the pressure transient of a hydrogen–oxygen reaction. This may form part of the fire hazard analysis report. By adopting a triple containment philosophy, the basic principle for safety is fulfilled in the case of a hydrogen/deuterium CNS. The moderator chamber (i) is surrounded by a vacuum container (ii), which is again enclosed by a gas blanket (iii). If monitored by instrumentation, any breach of the barrier can be quickly detected and rectified. The blanket gas could be any inert gas such as N_2 or He. Around components exposed to cryogenic temperatures, He is the only practical choice as a blanketing gas. Even with the most effective blanket and containment design, a postulated initiating event of a potential explosion may still be necessary to be analysed for regulatory review. The safety analysis needs to prove that the estimated maximum pressure can be withstood by the containment and thereby prevented from causing unacceptable damage to any reactor SSCs important to nuclear safety.

The storage tanks of hydrogen are pressure vessels. In many countries, pressure vessel regulation requires regular inspection, that may involve emptying the tank. It might be justifiable to consider applying exemption for this type of conventional inspection, to avoid potential safety risk during such activities. Alternatively, the inspection may include ultrasonic measurement for the vessel wall thickness. Assuming the hydrogen tank is doubled-walled with a blanketing gas in between, the gas gap may be made accessible for visual inspection and ultrasonic measurement. One of the benefits of a double walled barrel with blanked gas is that a breach can be detected before it is a problem (by measuring deviations in the blanketing gas).

[20] Guide to Safety of Hydrogen and Hydrogen Systems (ANSI/AIAA G-095A-2017), https://arc.aiaa.org/doi/book/10.2514/4.105197.

7. INSTALLATION AND COMMISSIONING

This section deals with installation and commissioning of CNSs at neutron sources. After installation of the CNS assembly and prior to commissioning, the process systems have to be pre-operationally tested, first as individual sub-systems, and then in an integrated manner. On completion of pre-operational testing, commissioning can commence. This may be divided into two major stages: cold commissioning (without reactor/accelerator power) and hot commissioning (at reactor/accelerator power). Special consideration has to be given at the early stage of installation to the cryogenic piping between the CNS on the reactor/accelerator side and the auxiliary systems to make the routing as short as possible, and to enhance the performance of the CNS.

7.1. INSTALLATION AND PRE-OPERATIONAL TESTING

The installation process needs to allow for leak tightness testing at every step, wherever possible, so that a leak can be identified and fixed at the earliest opportunity. Even very small leaks can be of great concern: for example, a small amount of air entering the cryogenic system can cause catastrophic failure of a He turbine. After installation, come the pre-operational tests, which are conducted in sequential stages, from individual sub-system testing (e.g., the vacuum system, the gas blanketing system, …), progressing to more integrated system testing (e.g., the cryogenic system, which requires an operational vacuum system and gas blanketing system), until all the CNS systems are ready for cold commissioning.

On completion of pre-operational tests, the integrity of the installation and all safety and process functions of the CNS systems are verified. Moreover, the full functionality of the control system, including alarm and fault response and emergency stop, is also verified. It is sound practice to verify the systems' response to a range of fault scenarios, such as loss of cooling water, loss of instrument signal, malfunctioning valves, etc. Whether such tests are conducted by verification of response to a physical failure or by manipulation of electronic signals to test response is subject to the engineers' best judgement.

Considerations ought to be given to the timing of loading hydrogen or deuterium gas into the moderator system, because of the potential for explosion or fire. Typically, He is loaded first as a 'dummy' test gas. Hydrogen or deuterium gas is only loaded after the completion of all operation tests relevant to hydrogen safety.

7.1.1. Considerations at research reactors

In most cases, the CNS assembly is installed in a research reactor vertically, or in a beam port horizontally. Any potential interference with the surrounding SSCs in the reactor has to be thoroughly assessed as part of engineering design.

The operational nature of the CNS is distinct from other reactor systems in that its systems and components are operated at cryogenic temperature in high vacuum to deliver the required performance. A clean environment and associated procedure are therefore needed for installation to proceed. It is suggested that installation of the CNS assembly be carried out after other major works are completed at the research reactor.

While installation of a CNS assembly in a new research reactor can be conducted in a logical sequence in a readily accessible environment, a retrofit or replacement CNS in an existing research reactor has to overcome the challenges of lengthy reactor shutdown, high dose rate in an activated environment, handling activated components, and disposal of radioactive waste.

7.2. COMMISSIONING

On completion of pre-operational tests, CNS commissioning can commence. The CNS commissioning needs to meet the following objectives:

(a) To validate that the system conforms with all the assumptions made in the safety analysis report;
(b) To verify that the installation and function of the CNS is commensurate with the performance requirements and intent of the design;
(c) To provide the baseline data for the safe and reliable operation of the CNS in the future;
(d) To characterize the performance of the CNS for contractual verification and for the neutron scattering users.

Commissioning may be divided into two stages: cold commissioning where all the CNS systems are integrated and operated without heat load by keeping the reactor/accelerator in a shutdown state, and hot commissioning where the CNS systems are operated up to full reactor/accelerator power. During cold commissioning, CNS process functionalities and transitions such as moderator liquefaction and evapouration, as well as reactor/accelerator interlocks, alarm and fault responses, and the emergency stop associated with the CNS are verified. The reactor/accelerator power ought to be raised incrementally in the hot commissioning program, where appropriate tests are conducted at each power level. When the reactor/accelerator reaches full power, the CNS process functionalities have to be verified with a focus on transitions under full heat load. It may be noted that the scope for testing alarm and fault responses and of the emergency stop is restricted because frequent reactor/accelerator trips are unlikely to be permitted. Nevertheless, some essential tests, such as CNS response to loss of reactor/accelerator power or reactor response to loss of CNS control, are to be performed with full power.

The sequence of tests within each stage will be given in the order in which they will be carried out. The sequencing of the tests ought to be determined on the basis of:

(a) Prior testing of components or systems that will be required later for the testing of other systems;
(b) Keeping certain systems operational during tests for safety or interrelated performances;
(c) Grouping those tests that need to be completed before continuing to the next stage. No test may proceed unless the required previous steps have been successfully completed.

Documentation is a critical part of the commissioning program, which is intended to describe the commissioning activities, provide results and their evaluations, resolve deviations, fulfil obligations under the reactor licence, and permit the transfer of responsibilities to the operations team. A summary of commissioning test results needs to be appropriately incorporated into the operating procedures and safety analysis report.

7.3. CHARACTERIZATION AND BENCHMARKING

Characterization, here, refers to the measurements made of the performance of the CNS during commissioning. Benchmarking is the validation of the design calculations against the characterization measurements. Benchmarking the key performance parameters of the CNS supports the instrument operation and (re-)design and, also, helps to recognize potential problems with the source, neutron beam transport, etc. Keeping this in mind, the CNS characterization is a process that has to be considered from the very beginning; i.e., starting from the feasibility study (Section 3). The following two subsections give examples of

characterization and benchmarking exercises conducted at a research reactor and short pulse spallation source.

7.3.1. An example at a research reactor: OPAL, Australia

For a reactor based CNS, characterization and benchmarking of its performance verify the design specification, validate calculation methodologies, and provide a reference for operations and future improvements. While demonstrating thermohydraulic stability is an integral part of commissioning, key neutronic parameters, including nuclear heat load, cold neutron spectrum and gain at long wavelengths, need to be measured with a purposeful plan.

Nuclear heat load and thermohydraulic stability are closely related. The heat load of the CNS is a critical design specification for sizing the capacity of the He cryogenic system, which requires verification by measurements. Nuclear heat load can be measured at steady state by using thermal balance in the He cooling system. By measuring heat load at incremental reactor powers, the nuclear heat load normalized to reactor power can be estimated. Based on the normalized nuclear heat load, the non-nuclear heat load can also be readily estimated (see for example the OPAL reactor's CNS heat load measurements in Figure 22).

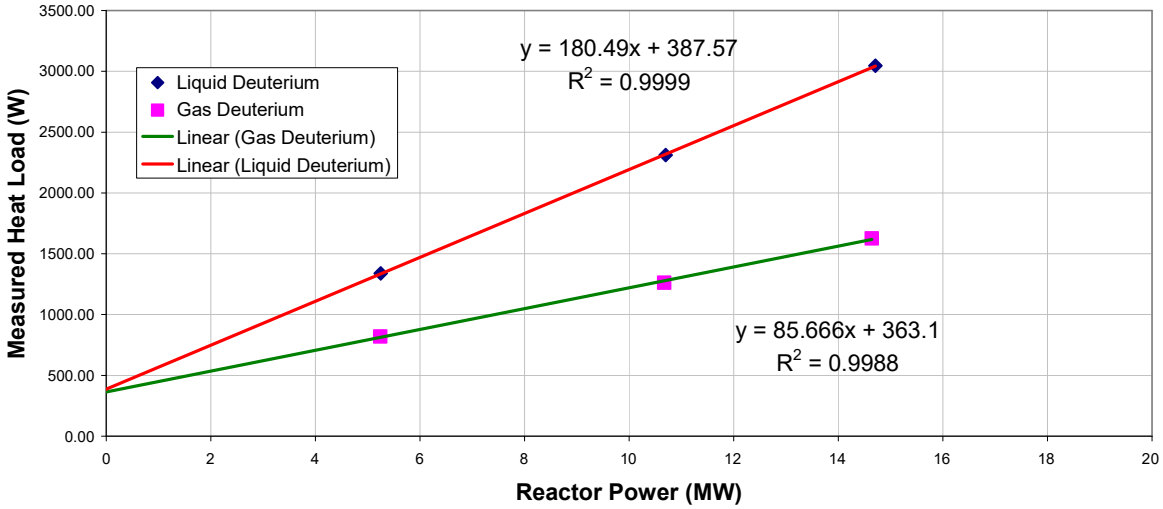

FIG. 22. Measured heat load on the OPAL CNS in-pile by cryogenic He thermal balance. Linear fits indicate nuclear heat load (W/MW) by the slope and non-nuclear heat load by the offset (W) (courtesy of W. Lu, ANSTO).

The CNS is designed to deliver cold neutrons for neutron scattering research. The gain at long wavelength demonstrates how effective the CNS is in shifting the neutron spectrum from thermal to cold. The cold neutron spectrum can be obtained by time-of-flight measurements at low reactor power, preferably taken at a location before the neutron guides. If time-of-flight measurements are taken at the end of neutron guides, the effects of the neutron guides on the cold neutron spectrum need to be corrected for. If it is feasible to take the cold neutron spectra between the two CNS states, i.e., with and without the moderator, the gain can be directly ascertained. By using neutron scattering instruments where neutron wavelength can be selected or scanned, the gain can be ascertained even at the end of neutron guides. An example of such gain measurements on the OPAL CNS is shown in Figure 23, where multiple instruments at the end of neutron guides showed CNS gain above the Maxwell–Boltzmann theoretical estimation due to the absence of any moderator in the CNS volume in the no-moderator case.

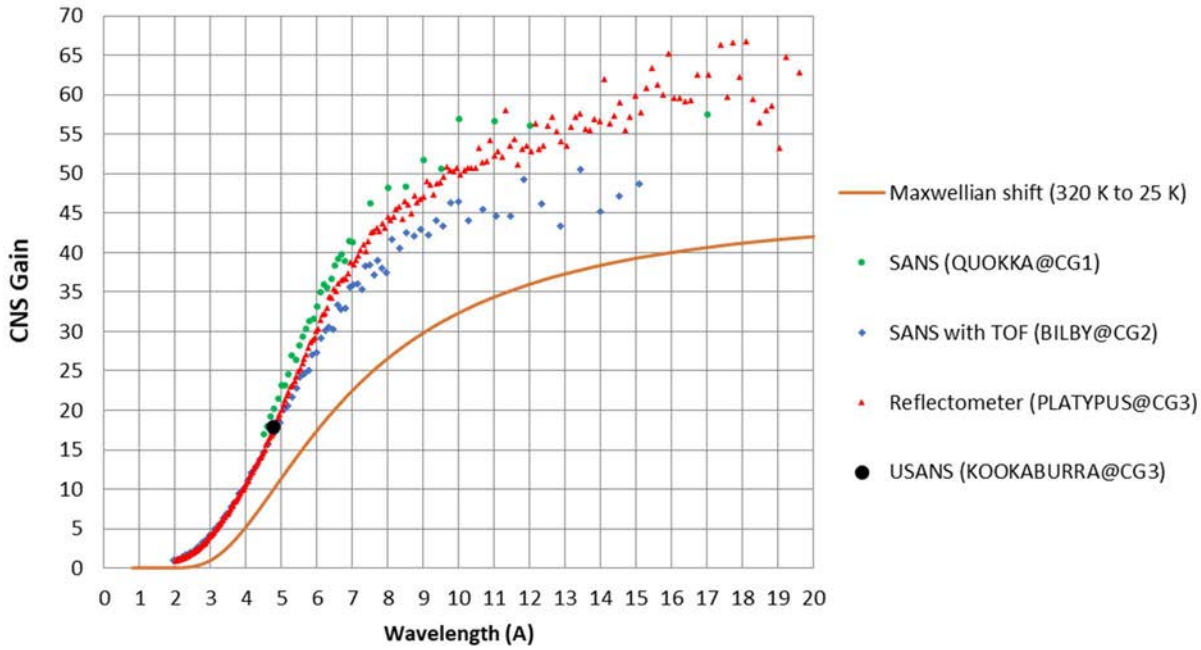

FIG. 23. OPAL reactor CNS gain measured by the instruments Quokka, Bilby, Platypus, and Kookaburra: moderator to no-moderator ratio as of June 2015 (courtesy of W. Lu, ANSTO).

7.3.2. An example at a short pulse neutron source: ISIS Facility, UK

The following describes a program that involved the neutronics specialists and instrument scientists at the ISIS Facility to benchmark neutronics simulations of TS-1 performance [187]. This was done within the scope of a major project to update the 38-year-old target, reflector, and moderator assembly in ISIS TS-1. The ISIS TS-1 hydrogen moderator (pre-2019) was operated at 20 K and its dimensions were 12 cm (height) × 11 cm (width) × 8 cm (thick). Figure 24 shows the measured and simulated flux profiles for one of the reflectometer instruments (CRISP) looking at this moderator. There was a large uncertainty with simulations for the pre-2019 hydrogen moderator as the *p*-/*o*- isomer ratio was not precisely known. There were many attempts to make measurements of this ratio by various means [188] and to benchmark simulation results. The *p*-hydrogen fraction in TS-1 hydrogen moderator was finally determined to be 80%, and this value was used in the simulations.

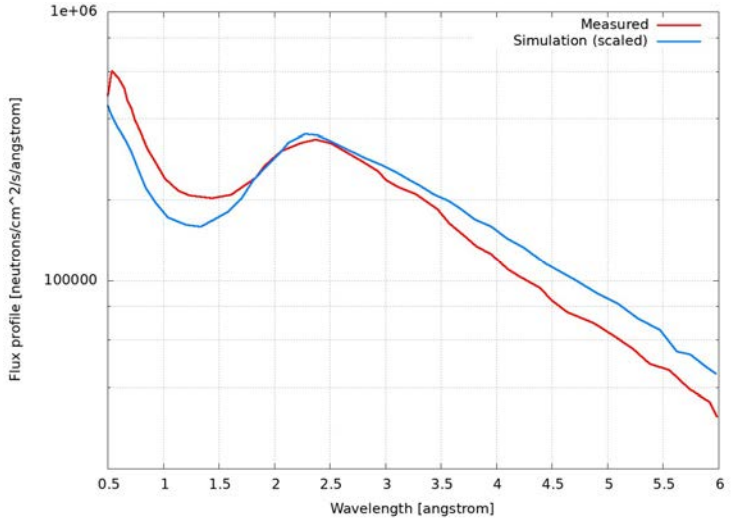

FIG. 24. Measured (red line) and simulated (blue line) neutron flux as a function of wavelength for the CRISP reflectometer instrument (ISIS TS-1 pre-2019 liquid hydrogen moderator). The simulated profile was scaled by a factor of 0.7 (courtesy of R. Bewley, ISIS Facility).

In the case of a CNS at a pulsed neutron source, such as the ISIS Facility, the key performance parameters are the peak and time-averaged brightness (Section 4.1.2). However, from the point of view of neutron beam instrument scientists and visiting users, the key performance parameters are neutron intensity on their samples at the instruments and neutron pulse time profiles (time resolution). Therefore, characterization and benchmarking usually involve collaboration between the neutronics specialists at the facility and scientists at the instruments. The neutronics specialists and engineers will design the CNS (based on set of requests from instrument scientists) using modern Monte Carlo codes (such as MCNP [1]) to characterize the source and to produce the output ready to be used by instrument scientists for detailed neutron tracing from the moderator face to the neutron scattering instrument using specialized MC codes, such as McStas [189] or VITESS [190].

Using a calibrated bead monitor [191], absolute fluxes at the sample position together with the time structures for the TS-1 moderators were measured for some instruments and compared to corresponding simulations. Pulse time profile measurements were limited to instruments with back scattering diffraction detectors, as the peak shapes in this case are practically completely dominated by the moderator. The procedure for extracting useful results is not straightforward: a standard diffraction calibration sample, usually CeO_2 powder, was measured in backscattering diffraction. Then, a McStas simulation was performed for the instrument using a model CeO_2 McStas powder sample. The experimental and simulated patterns were then fitted in the profile fitting code GSAS [192] using the Le Bail method (which fits an independent scaling factor for each diffraction peak) [193], and then the full-width-at-half-maximum (FWHM) of the peaks was extracted. Figure 25 shows the measured and simulated FWHM values of pulse time profiles for one of the neutron diffraction instruments, PEARL, that looked at the ISIS TS-1 liquid methane moderator. The ISIS TS-1 liquid methane moderator (pre-2019) was centrally poisoned with a single Gd foil operated at 110 K. The moderator volume was approximately 0.5 litre (moderator thickness = 45 mm). As seen in Figure 25, the FWHMs of the simulated baseline is marginally narrower than the measured FWHMs but only by ~3–4%.

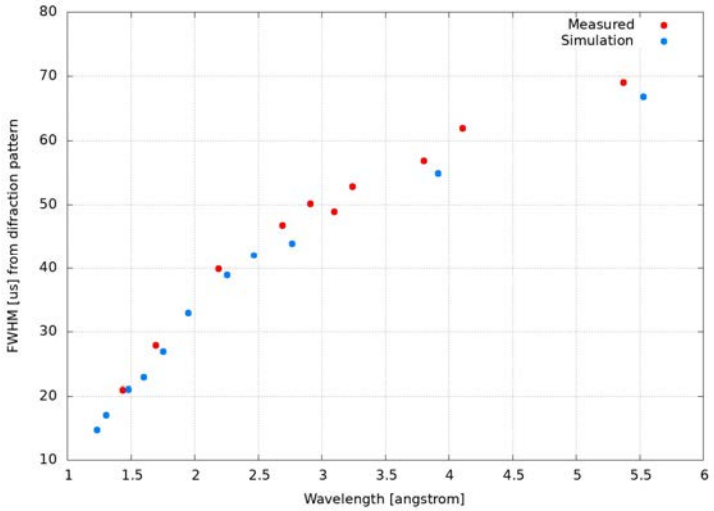

FIG. 25. The FWHM of measured (red dots) and simulated (blue dots) neutron pulse time profiles (as a function of wavelength) for the PEARL instrument looking at the ISIS TS-1 pre-2019 methane moderator (courtesy of R. Bewley, ISIS Facility).

As can be seen, the characterization and benchmarking are not trivial tasks, but the validation of a CNS design and the simulation methods (and techniques) used is of critical importance.

8. PROJECT MANAGEMENT

Cold neutron sources are installed at research reactors and various types of accelerator based neutron sources. Cold neutron sources show a wide range of complexity, technical solutions, and moderator substances. Nevertheless, there are general principles that have to be observed for the implementation of CNS projects from design through manufacture, testing, installation, licensing to operation. Chance of success are enhanced by using a well-defined project management methodology. Among the popular systems are PRINCE2[21], which is a process based method [194], and the systems of APM[22] and PMI[23], which are frameworks for managing projects [195, 196]. A high-level overview of the OYSTER CNS project at the TU Delft HOR reactor is given in Refs [94, 100].

8.1. QUALITY MANAGEMENT SYSTEM

A Quality Management System (QMS) of the CNS project has to be used, providing objective documentary evidence that the CNS production will be fulfilled in time and according to the requirements of the project specification. The QMS has to cover the following main fields:

(a) Project management plan: (i) Project management approach; (ii) Project scope; (iii) Communications management plan; (iv) Procurement management plan; (v) Deviation management plan; (vi) Reporting;
(b) Project schedule and milestones list (witness and hold points of inspection);
(c) Risk management plan: Defining risk criteria, risk assessment, and treatment;
(d) Quality plan: The quality plan is used for the process of manufacturing and testing of the CNS project. All quality relevant documents, drawings, test reports and other type of data have to be stored in a comprehensive documentation software. Information is typically stored on a mirrored double disk server as well as on back-up hard drives, and is password protected, for authorised users only.

8.2. DESIGN

For the design phase, the following items have to be considered:

(a) Design concept inputs and requirements;
(b) Design conditions and requirements: (i) Neutronic, thermohydraulic, and structural analysis calculation computer codes and modelling qualification; (ii) Materials definition and acceptance criteria; (iii) Design support tests and prototypes;
(c) Codes and qualification: (i) To assure correctness of calculated results, computer codes used for the structural analysis design calculations need to be qualified; (ii) The thermohydraulic design calculation codes to be used have to be qualified; (iii) Material acceptance criteria are subjected to analysis to meet the design strength and lifetime requirements; (iv) All engineering calculations have to be performed by suitably qualified and authorised personnel;
(d) Project interfaces. There are two groups of interfaces during the design: (i) Interfaces within the CNS systems; (ii) For research reactors, interfaces between the ‘in-pile assembly’ of the CNS and the reactor systems. Each group contains parameters, which need to be maintained in agreement between different systems during the design process. Agreement means providing project requirements at any changes while systems

[21] PRINCE2: Projects IN Controlled Environments, https://www.axelos.com/certifications/propath/prince2-project-management.
[22] APM: Association for Project Management, https://www.apm.org.uk/.
[23] PMI: Project Management Institute, https://www.pmi.org/.

designing. These 'cross' parameters influence the design of neighbouring systems and have to be traced: (i) CNS interfaces at different design areas; (ii) CNS joints; (iii) Neutronics; (iv) Thermohydraulics; (v) Materials; (vi) Mechanical and structural analysis; (vii) Safety assessment; (viii) Process systems; (ix) Reactor system interface;
In the CNS 'in-pile assembly' interface with the reactor pool components layout, the delimitation of responsibilities has to be clearly defined in the technical documentation;

(e) Prototyping. The design support tests and prototypes ought to be done for the development of production of unique components (e.g., moderator chamber) and functional tests of prototypes (e.g., thermosiphon loop). Manufacturing procedures have to be worked out for the moderator chamber construction in order to meet specific design requirements. The manufacturing procedure needs to be improved until meeting the requirements on welding, wall thickness uniformity, shape, and weight. Particular tests have to be done to check parameters. After manufacturing, the moderator chamber components (moderator cell, He jacket, and displacer with tubes) and later moderator chamber assembly are subjected to a pressure test, a thermal-cycling test, and a vacuum tightness test;

(f) Manufacturing. Late design changes ought always to be avoided. Therefore, the manufacturability of a design needs to be checked as early as possible. This can depend on material properties (see Section 4.5.5). Heat treatable Al alloys, like Al 6061-T6, are prone to warpage during machining; this is especially true of large, thin-walled components. (Non-heat treatable Al alloys do not tend to warp, which is a benefit.) Moreover, Al 6061-T6 is difficult to weld. Frequently, heat cracks, pores, and voids occur during welding. In order to understand and to prevent this phenomenon, a welding test is very important.
For reproducibility, it is recommended that the selected parameters be documented by a welding process specification. Furthermore, for the quality of the welding process, cleanliness is vitally important. First, it needs to be guaranteed that the surfaces of the parts are free from grease. Second, the oxide layer needs to be removed by pickling. Third, a rebuild of the oxide layer needs to be prevented by drying and vacuum packing of the components. Also, the cleanliness process needs to be documented in a cleaning specification. Furthermore, it ought to include the specification of the chosen welding methods: (i) Electron beam; (ii) TIG; (iii) Friction.

8.3. MANUFACTURING AND ASSEMBLY REQUIREMENTS

A set of acceptable quality levels[24] for components will be derived to satisfy the engineering design, itself constrained by national regulations, standards, and codes in force, governing, e.g., the choice, mechanical properties, and performance under irradiation of the materials selected; pressure vessel regulations; nuclear regulations; explosive atmosphere regulations; etc. The codes will vary in different systems within the CNS (e.g., in-pile vs. out-of-pile) and in different countries. As some components may be manufactured by different techniques by different manufacturers, the final quality levels for each component may not be known in their entirety until the stage of contract bidding and award.

Some of the common codes are discussed in Sections 4 and 6, and some practical experience is given in Annex III. The following list provides details concerning quality, qualification, and documentation required:

[24] Philip B. Crosby, a leader in zero defect manufacturing, defined quality as "…conformance to requirements", where the requirements are set by the specifications, performance expectations, and by engineering and regulatory restrictions.

(a) Quality levels. During manufacturing the appropriate quality level has to be applied for the different main components of the CNS; e.g., vacuum containment, ‘in pile assembly’, and ‘out of pile systems’;
(b) Qualification of manufacturer(s). The manufacturer and the subcontractors need to be qualified and need to provide information about qualification of personnel, processes, facilities, and equipment;
(c) Manufacturing documentation. For QA and QC of manufacturing, the following documents will be applied: (i) Requirements of the contract for items purchase; (ii) Quality assurance and quality control programs of the manufacturer.
Whenever necessary, the manufacturer(s) has to accommodate their QA and QC programs to meet the above-mentioned standards/documentation.

8.4. PERFORMANCE TEST

A full performance test prior to installation and commissioning is normally impossible because the primary neutron source is missing, and it is usually also not possible to test with liquid hydrogen. However, a simplified performance test could still help to verify assumptions. With a pressure loss measurement, parts of the fluid dynamic calculations can be checked. A quench test can simulate the fast load changes expected during cool down and warm up. The number of quench cycles performed needs to correspond to the number of expected shutdowns in the lifetime of the moderator. A burst test of the moderator vessel can help to find out where the real load limit is. By using liquid nitrogen, the effect of cryogenic temperatures (e.g., embrittlement) can be considered. However, the embrittlement by radiation cannot be tested.

8.5. FACTORY ACCEPTANCE TEST

The completed main assemblies of a CNS have to pass the Factory Acceptance Test (FAT) according to the approved testing procedure prior to delivery. The FAT involves verification of pre-determined parameters or expected performance by testing the device under factory conditions. These conditions have to have been set, jointly with the end-user, in the acceptance criteria during the design phase.

8.6. QUALITY CONTROL AND INSPECTION

The following list provides details concerning QC and inspection that need consideration:

(a) The quality of all products is controlled during production phases. All technical documentation and manufacturing process are inspected by the QA supervisor. The supervisor is the responsible for record and collect all deviations from product specifications during the manufacturing process;
(b) Non-conformities have to be submitted to the inspection team for evaluation and further approval (e.g., ‘repair’ or ‘use-as-is’) prior to the continuation of the work;
(c) Manufacturers have to submit together with the finished unit, subassembly, etc., a completed quality record including, as minimum, the following:
    - Full material reception inspection plan;
    - Full production, inspection, and testing plan
    - A listing of the as-built configuration of each item;
    - Test reports;
    - Non-conformities;
    - Punch list (capturing any abnormality not described in manufacturing specification);

- Corrective actions;
- Grading of special processes and executive staff;
- Evaluation of the manufacturer;
- Used procedures;
- Conformance certificate;

(d) After the final FATs have been completed and the approval for delivery issued, the history docket of the as-built document package has to be prepared. The history docket needs to be well structured for easy search, contain all manufacture and testing results, and change and deviation reports in one document package;

(e) After delivery and on-site installation, the as-built document package has to be updated with the SAT documentation.

9. OPERATION AND RELIABILITY

The CNS is an integral part of the reactor facility or accelerator neutron source and needs to be operated as such. The CNS is often controlled by specialists under its own control system. As such, it is desirable to maintain a specialist knowledge base in the organisation through training and mentoring for the long term. In the case of research reactors, the reactor response to the trip of the CNS's cryogenic system is an important feature in the system design. In reactors dedicated to neutron beam research, it is often the case that the reactor would trip if the CNS cryogenic system trips because there would be no need to operate the reactor without the CNS. In some of those facilities, reactor shutdown may be required to prevent overheating of the CNS moderator container. For multi-purpose research reactors, however, it may be desirable to continue operating the reactor without the CNS so that irradiation services and thermal neutron beam research are not disrupted. In such cases, design provisions have to be made to maintain cooling of the CNS structure, if required. It is feasible to design the cryogenic system in such a way that the CNS can transition between shutdown and operation, in both directions, with minimal impact to reactor operation (e.g., OPAL at ANSTO and CARR at CIAE).

In the interest of the neutron beam users, it would be valuable to implement a program of continuous improvement and optimisation of the CNS. Such a program can include:

- Setting a performance objective in the CNS's reliability and availability;
- Learning from past process faults and failures, which are often the most valuable source of local knowledge;
- Constantly monitoring the process and analysing operation data and tracking the trends in performance of individual subsystems and the entire CNS (e.g., Figures 26 and 27);
- Implementing optimisation projects incrementally;
- Strengthening and improving operating and maintenance procedures.

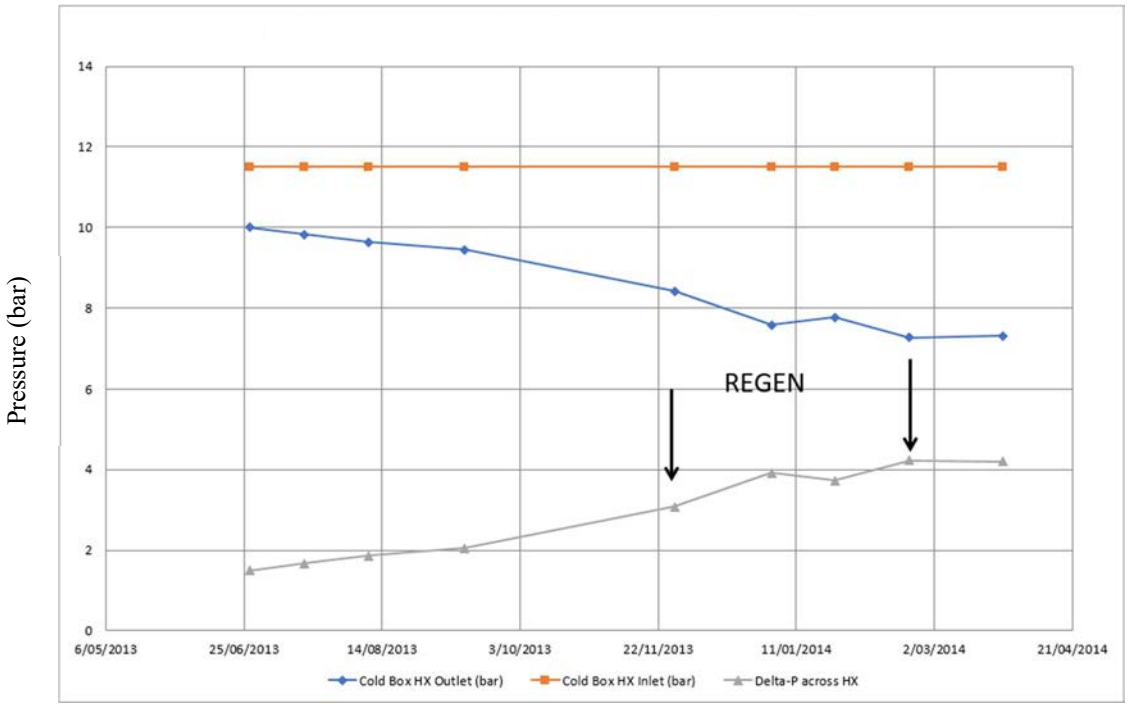

FIG. 26. The pressure drop across the cold box heat exchanger (HX) in the OPAL CNS (ANSTO) was observed to increase over time. Regeneration of the charcoal adsorber, a part of the HX circuit, made no difference, suggesting the blockage was not impurity related. It was concluded that the blockage was most likely caused by charcoal dust blocking a particle filter. System performance was fully recovered by opening the cold box and replacing the filter (courtesy of W. Lu, ANSTO).

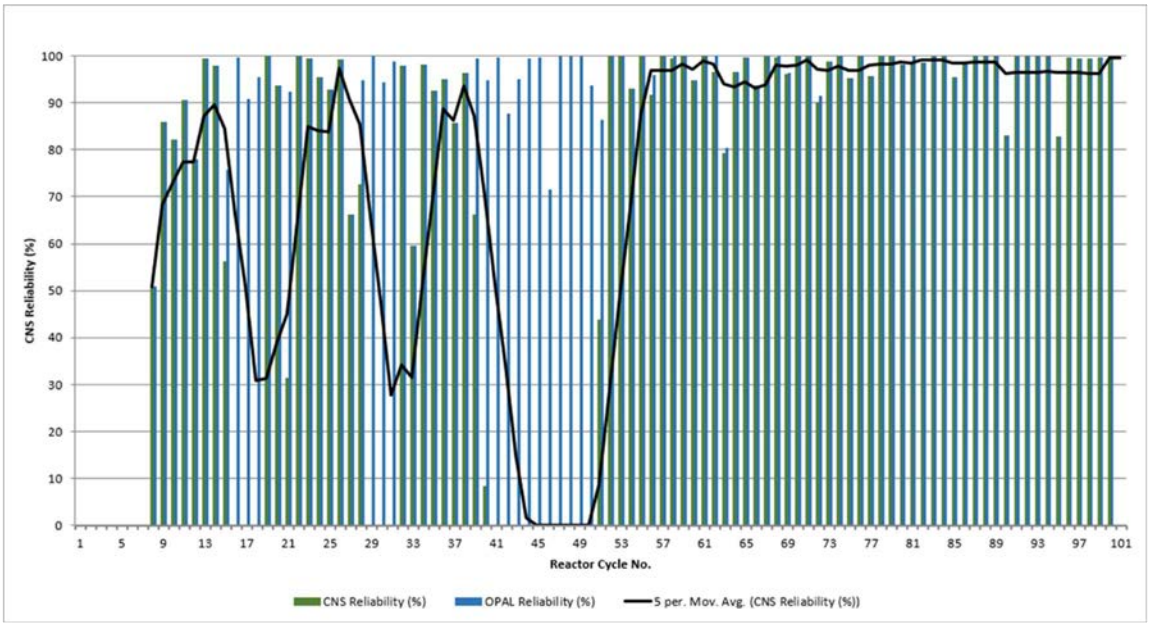

FIG. 27. The OPAL CNS was plagued by a design fault in the helium cryogenic system in its early years. After the fault was identified as being related to the helium compressors, it was fixed, and a comprehensive maintenance strategy was also implemented. Reliability of the CNS has reached and stayed at practically 100% thereafter, in the years up to 2023 (courtesy of W. Lu, ANSTO).

One example of the objectives of such a program is to improve the capability of the CNS process system to quickly recover from a power outage without jeopardising the CNS safety case. A quick recovery back to operation could make the difference between continuation of the neutron beam experiments and premature termination due to reactor poison-out.

Staff need to be aware of radiological safety during maintenance work. Some components of the CNS process systems may be directly activated or contaminated by radiologically active substances during operation. As repairs to a CNS can be lengthy and difficult, high reliability is crucial for CNS operation, and is underpinned by thoughtful design, a sound maintenance strategy with adequate resources, and management support to implement it. Built-in redundancy can enhance long term reliability. For example, spare temperature sensors may be installed in the cryogenic system during assembly where in-situ replacement is disruptive and difficult. The maintenance strategy has to identify major failure modes, ranked by risks, and specifies scheduled actions to prevent failures and minimize risks. Reliable access to spare parts is a crucial consideration in the maintenance strategy. Typical process faults include instrumentation error, leaks and vacuum failure, malfunctioning valves, and unreliable supplies of power, cooling water, or compressed air. For a He cryogenic system, as long as the gas purity is under control, corrosive degradation is minimal, and, therefore, frequent replacement of plant items, such as compressor oil and coalescers/filters, is not necessary, unless abnormal conditions are observed. Regular regeneration of the charcoal adsorber can ensure high gas purity in a He cryogenic system and is best performed in situ. Periodic charcoal replacement may be necessary depending on local conditions. Engineering provisions for conducting charcoal replacement, whether designed for from the beginning or arranged retrospectively, is strongly recommended.

For a research reactor, modifications to the existing configuration need to be categorised according to their impact on nuclear safety and assessed in a due process like any other modifications to the reactor facility. The IAEA publication SSG-24 discusses this topic [185].

10. LIFETIME, WASTE, AND DECOMMISSIONING

Cold neutron sources are considered as part of the nuclear installations in the case of reactor based neutron sources or as part of the target–reflector–moderator assembly in the case of accelerator based neutron sources. By this they are subject to the authorisation procedures and licensing of these facilities in the corresponding countries.

10.1. LIFETIME

The life-limiting neutron 'dose', as measured by dpa (see Section 4.5.4), received by the CNS depends on the strength of the neutron source and the neutron spectrum. Hence, the lifetime of a CNS is strongly related to:

(a) The activation and alteration of engineered materials (mostly Al alloys; see Sections 4.5.4 and 4.5.5), which depend on the operation of the primary neutron source;
(b) Mechanical stress due to thermal expansion of the materials on cooling and heating, which can restrict the lifetime of CNS materials and components.

Based on these considerations, average lifetimes of the engineering parts of reactor based CNSs have been calculated to be in the range of ~10–15 years based on up to 200 days of source operation per year. Longer lifetimes are given at spallation sources under certain conditions; e.g., at the UCN facility of PSI in Switzerland, the CNS is expected to run as long as the facility, which is expected to be at least 20 years. Regular upgrades and refurbishments of the operated CNS systems allow for safe and prolonged operation and lifetimes; e.g., the CNS at the BER II reactor in Berlin, Germany had achieved a total operation time of 28 years upon closure of the facility in 2019.

Another restriction on the lifetime of a CNS is degradation of the hydrogenous material by formation of radicals in the case of organic moderators, such as methane, mesitylene, or propane [197]. Depending on radiation levels, exchange of the moderating material may already have to happen after some 100 hours of operation. To account for this problem, periodic renewal of the moderator inventory is usually correlated with the operational schedule of the neutron facility (e.g., at ISIS). This issue with hydrocarbon moderators in general is discussed in Section 11.1, the specific case of mesitylene in Annex I, and the operational experience at the ISIS Facility in Annex III. Another solution is a pelletized cold moderator: the complex of cold neutron moderators of the IBR-2 reactor at the Joint Institutes of Nuclear Research, Dubna, Russian Federation, based on frozen beads of mesitylene and *m*-xylene has been operated successfully since 2012. The pelletized moderator operates during one reactor cycle (10 cycles per year), which usually lasts 11–14 days, as a result of which the absorbed dose of ionizing radiation is ~110–150 MGy, and the pellets are then replaced (see Section 11.1).

10.2. REPLACEMENT

In the case of the operation of a CNS in a nuclear reactor, restrictions on using only materials that have been certified to very high levels may have to be followed, which may need a prolonged planning and procurement phase before manufacturing and replacement of the CNS. This may lead to total times for the planning, construction, and installation phases of up to several years, and this has to be taken into account when calculating expected lifetimes of the CNS. Due to the different regulations in force and safety requirements at accelerator facilities, exchange or replacement of CNS systems is usually less time consuming.

A major reason to replace a CNS system, besides radiation induced lifetime, arises with major upgrades of the neutron source (reactor or accelerator driven) and installations of new beam tubes or other devices within the source. In addition, new developments in the nucleonic performance of CNS systems may lead to replacement of an operating CNS (e.g., exchange of one moderator vessel for another of a different geometric design, see, e.g., Refs [198] and 199]) or the decision to use a different moderator material (e.g., liquid hydrogen or solid deuterium instead of solid methane). This is usually considered within major upgrade programs of the corresponding neutron sources after a decade or longer of operation.

10.3. WASTE AND DECOMMISSIONING

The IAEA has published reports on decommissioning that may provide useful details in planning the approach for a CNS in a nuclear or accelerator facility [200, 201].

Replacement of CNS systems or closure of the corresponding neutron facility requires decommissioning of the CNS. In general, the decommissioning of a CNS forms part of the general decommissioning activities of a nuclear or radiation facility and follows the national radiation safety and nuclear operation regulations. It needs a good level of planning and interaction with the corresponding local authorities. In particular, in the case of a CNS operated in a reactor core, strict procedures and regulations are given. Depending on the expected level of activation, a CNS at an accelerator-based sources may be decommissioned with less restrictive boundary conditions, but any activated material to be removed will have to be handled according to the national regulations.

In Annex V of this publication the results of a ‘Questionnaire regarding the Lifetime, Waste and Decommissioning considerations for Cold Neutron Sources at research neutron facilities’ is given with certain specific information on these aspects collected at a few facilities.

11. RECENT DEVELOPMENTS

In the years 2014–2019, a Coordinated Research Project (CRP) F12026 entitled 'Advanced Moderators for Intense Cold Neutron Beams in Materials Research'[25] was run by the IAEA. It had three specific objectives:

(a) Improve the modelling of neutron source/instrument performance;
(b) Identify and characterize new materials and geometries suitable for use in neutron moderator systems;
(c) Design and/or deploy new cold neutron moderators to improve performance of members' facilities.

A brief summary of the activities of this CRP has been published [202]. The following describes in a little more detail some of the activities that took place towards those goals both within the CRP itself as well as outside of it.

11.1. SOLID COLD MODERATORS

Although methane is an excellent cold moderator, a replacement for solid methane as a cold moderator is sought, due to the intrinsic radiolysis, swelling, and 'burping' of this material. Methane has both a higher hydrogen density than liquid hydrogen and, in its liquid and disordered crystalline phase, an inelastic spectrum with a strong contribution from the low-frequency dynamics characteristic of quasi-free rotational disorder of the methane molecule. Any replacement material for methane requires similar hydrogen densities and similar density of low-frequency vibrational/rotational modes ('density of states'). Some of the leading candidates for replacing methane include mesitylene (1,3,5-trimethylbenzene) and triphenylmethane, whose aromatic ring structures (Figure 28) help to resist free radical decomposition of the structure.

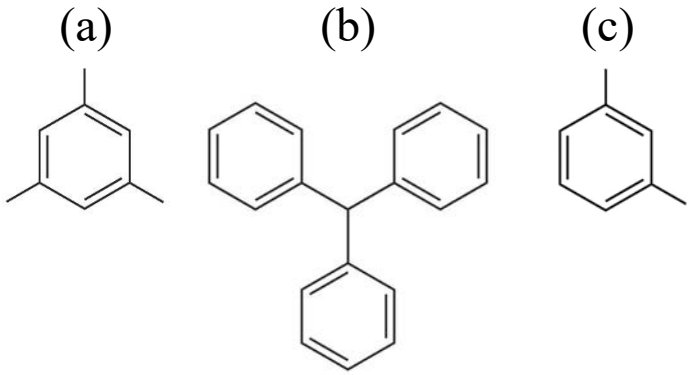

FIG. 28. Molecular structures of three 'methane-like' aromatic compounds used in cold neutron sources. (a) 1,3,5 trimethylbenzene (mesitylene) (b) triphenylmethane (c) 1,3 dimethylbenzene (m-xylene).

Triphenylmethane received attention from many groups during the CRP. Los Alamos National Laboratory performed measurements on triphenylmethane as a possible moderator and provided an analysis of the inelastic scattering [128]. The Comisión Nacional de Energía Atómica (CNEA), Argentina worked on the development of scattering kernels for triphenylmethane and its deuterated form and performed measurements of its total cross section at the Vesuvio spectrometer at the ISIS facility, UK [203]. Figure 29a shows that a continuum of modes from thermal energies (ca. 20 meV) downwards exists in triphenylmethane; it also

[25] https://www.iaea.org/projects/crp/f12026.

gives a comparison of the inelastic scattering cross sections of methane, triphenylmethane, and mesitylene.

Mesitylene was studied intensively during the CRP for use in both reactors and accelerators as a cold moderator [204]. The Low Energy Neutron Source (LENS) at the University of Indiana and CNEA validated a scattering kernel for the deuterated form. CNEA examined a 3:1 mixture of mesitylene and *m*-xylene (1,3 dimethylbenzene): the mixture of these two compounds reduces the tendency to crystallize, giving 'glassy dynamics' – an additional contribution to the dynamics at even lower frequency [205–206]. Similarly, inelastic and total scattering measurements were performed on triphenylmethane by J-PARC and LENS, and CNEA developed scattering kernels at different temperatures.

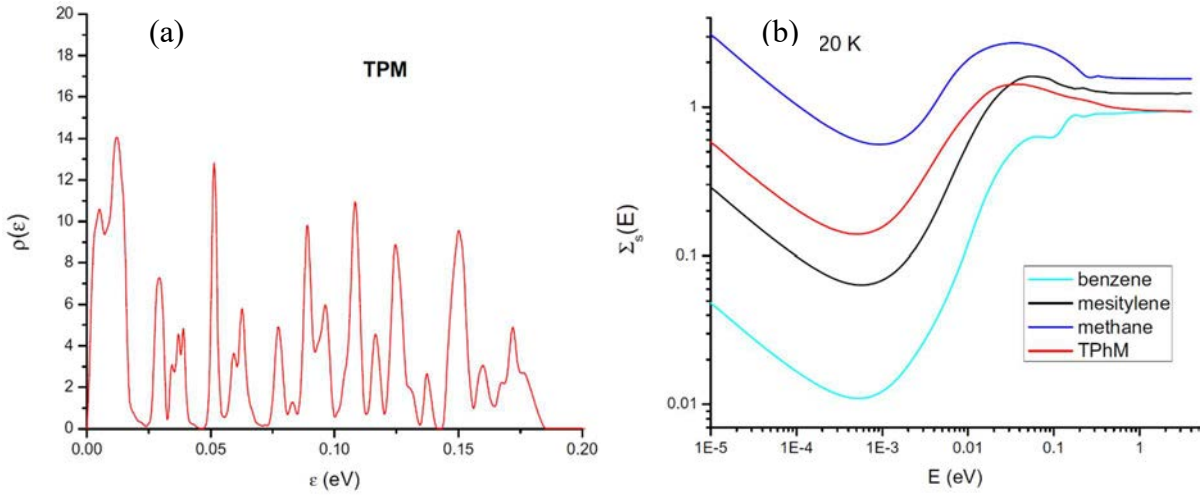

FIG. 29. (a) the density of states ρ(ε) of triphenylmethane from 0 to ca. 180 meV. There is a continuum below 25 meV. (b) Comparison of the macroscopic inelastic scattering cross sections $\Sigma_s(E)$of different solid cold moderator materials at 20 K, including triphenylmethane (TPhM). This figure by the authors of Ref. [204] is licensed under CC BY-4.0.

The slight loss of density of states in these other compounds when compared to methane in the low frequency region is compensated by increased resistance to radiolysis. While these materials are more resistant to radiolytic decomposition than methane, they also ultimately degrade, and some form of reforming or replacement of the material is required.

One solution is to use a pelletized aromatic compound with more resistance to radiolysis. Currently, the study of the effect of ionizing radiation on the radiochemical properties of mesitylene in the pelletized cold moderator of the IBR-2 research reactor is underway, which uses a mixture of *m*-xylene (1,3-dimethylbenzene) and mesitylene (1,3,5-trimethylbenzene) (Figure 28). The system has boosted long-wavelength ($\lambda > 4$Å) neutrons by up to 13-fold compared to the previous water-only moderator [207]. Depending on the radiation dose, the viscosity of the mixture after post-irradiation heating ranges from 1 up to 50 mPa·s. Such viscosities permit changing the working material in the cold moderator chamber without any problems. The maximum concentration of radiolytic hydrogen in the pelletized cold moderator of the IBR-2 reactor at different temperatures of this system has been investigated. The concentration of radiolytic hydrogen at a temperature of 22 K with an irradiation dose of 150 MGy does not exceed 0.1%. In the process of post-irradiation heating, radiolytic hydrogen begins to leave the mixture at a temperature of 115 K; its concentration reaches 50 mol %. The experiment determined that the concentrations of radiolytic hydrogen under inert He (the bead transporting gas) cannot lead to the production of an explosive gas mixture in the moderator chamber, both during its operation at reactor power at a temperature of 22 K, and during post-irradiation heating with the reactor out of operation. Upgrades of the system to continuous

filling, and to test the utility of triphenylmethane are possible. The latter, whose melting point is 365 K, is expected to have even better resistance to radiation damage and comparable neutronic performance to the materials already in use [207].

11.2. LIQUID COLD MODERATORS

The liquid moderators examined included the widely used hydrogen moderators, but also ethane and ammonia.

11.2.1. Liquid hydrogen moderators

In traditional hydrogenous moderators, the peak moderated flux typically lies within the moderator volume, whereas the neutron emission is dominated from the near surface due to the fact that, broadly speaking, the total cross sections of most materials increase with decreasing neutron energy once the neutron energy is below the nuclear resonance regime. Therefore, faster neutrons can typically more easily escape the moderator vessel than cooler, more moderated neutrons, a phenomenon known as 'spectral cooling'. However, this is not true of liquid hydrogen moderators in which the hydrogen is predominantly in the *p*-isomer (Figure 3). The development of low-dimensional *p*-hydrogen moderators was one of the focuses of moderator research during the lifetime of the CRP. Two important observations and characteristics of moderation in *p*-hydrogen led to this:

a) The spatial distribution of neutron flux within the liquid hydrogen moderator was measured at the J-PARC spallation source [208], which showed that a higher brightness existed on the side immediately adjacent to the target receiving the primary neutrons, with a similar but weaker effect on the opposite side next to the reflector. The centre of the moderator vessel was not as bright.
b) The 'filter-like' energy dependence of the scattering cross section of liquid *p*-hydrogen means neutrons with energies below 1 meV can readily escape out of the moderator vessel (a 'leakage moderator'). The mean free path is larger than 10 cm for neutrons with $E < 14.7$ meV [209] and the risk of 'up-scattering' is minimal (Figure 7).

At spallation sources, the majority of the neutrons, which in many designs have passed through a thin water pre-moderator (Figure 10), may be moderated down to cold energies (~5 meV) in 1–2 collisions, which occur within a comparatively thin depth in the *p*-hydrogen vessel [210] (Observation a above). This shallow moderation depth, coupled with the high transmission of cold neutrons through *p*-hydrogen means that 'low dimensional' vessel shapes can be used (i.e., forms with at least one long dimension) and that emission takes place effectively from throughout its whole volume [210] (Observation b) along one or more long dimensions. This enables moderator vessels in the form of like 1-d rods, and 2-d discs and butterflies [107]. Gains of ~4-fold may be possible when coupled with a suitably designed water pre-moderator and reflector [209–210].

Among the CRP members with spallation sources, both the Spallation Neutron Source's (SNS) project to support a second target station at Oak Ridge National Laboratory, USA and the baseline design for the European Spallation Source in Lund, Sweden were using low-dimensional moderators, whose design basis calls for ≫90% liquid *p*-hydrogen. Among CRP participants with research reactors, the most advanced progress towards use of *p*-hydrogen was at the Budapest Research Reactor (BRR). At the BRR, modification to their refrigeration system of their existing cold moderator to allow pre-cooling for 14 days in order to increase the *o*- to *p*- spin isomer ratio by natural relaxation showed cold neutron gains of 30% in their current

(unoptimized) cold moderator. Work was on-going during the lifetime of the CRP to build a rod-like *p*-hydrogen moderator with optimized form. As part of this a pinhole camera to map the spatial distribution of the neutron flux within the moderator was being developed. Within the project developing an accelerator-based neutron source at Forschungszentrum Jülich, Germany, recently a compact one-dimensional variable *o*-/*p*-isomer hydrogen moderator system has been developed and tested [211].

11.2.2. Accelerating relaxation of the hydrogen spin isomers

At 20 K, the equilibrium ratio of spin isomers is 99.8% *p*-hydrogen, but the natural relaxation rate from the room temperature ratio (where the *o*- to *p*- ratio is 3:1) is ~2% per hour [188]. Two commercial catalysts were known to accelerate the relaxation from *o*- to *p*-hydrogen: 'IONEX' (ferric oxide gel), and 'OXISORB' (chromia-doped silica). Both catalysts possess magnetic centres that decouple the nuclear spins in the hydrogen molecule. When the spins recouple, they tend to do so in the equilibrium form at the ambient temperature in which they find themselves. The structure of the surface of the two catalysts was determined in a collaboration between ORNL and ESS [212]. The ESS determined that a system based on ferric oxide gel was the more efficient of the two.

There are two active probes based on inelastic scattering to determine the ratio of spin isomers of hydrogen: Raman spectroscopy and inelastic neutron scattering. A Raman spectroscopy setup has been tested and is operational at ESS [213]. Experiments were planned to determine the amount of catalyst needed for the hydrogen loop as well as the speed of conversion outside of the radiation field [213]. It is likely that future *p*-hydrogen moderators will include online monitoring of the hydrogen isomer ratio, likely by Raman spectroscopy. Los Alamos has installed such a system in their operating hydrogen loop. At the ISIS Facility, UK, the ratio of spin isomers of hydrogen that had been extracted from the operating cold moderator on TS-1 and TS-2 was measured on one of the inelastic neutron spectrometers [188, 203] and improvements to the design were envisaged to increase the ratio beyond the observed 80% *p*-hydrogen. Similarly, at J-PARC, the ratio of spin isomers of the moderator while being irradiated by spallation neutrons was measured by Raman spectroscopy measurements of the boiled off gas [214] rather than the liquid, as the relaxation to equilibrium form at a given temperature is very slow and the change in physical state does not itself change the spin isomer. The conversion between the isomers under irradiation by neutrons as a function of energy has been reported in Ref. [215], where it was shown that the rate of conversion from *p*- to *o*- is not significant for neutrons of energies less than the difference in energies between the two ground states ($E < 14.7$ meV) but rises quickly thereafter. This is responsible for the steep 'filter-like' rise in the scattering cross section of *p*-hydrogen in this energy range (see Figure 7). Conversion rates under γ irradiation have been previously reported [216].

Dedicated moderator test stands were under development during the lifetime of the CRP at both ORNL and ESS. A new moderator test facility built for further development of *p*-hydrogen and other advanced moderators at SNS: a dedicated CANS [14] using ~2.5 MeV protons from an radiofrequency quadrupole linear accelerator with a Li target was being developed [217–218].

11.2.3. Other cool or cold moderator materials

Other possible moderator materials were examined, including ammonia. In its favour were said to be a fairly good resistance to radiolysis, good low-frequency dynamics, and, unlike hydrocarbons, a low tendency to polymerise [219]. Its disadvantage is the high absorption cross section of ^{14}N, so that any future system to be put into operation would likely be based on $^{15}NH_3$. Ammonia freezes at 185 K, so liquid ammonia may be useful as a cool moderator for

neutron scattering instruments requiring neutrons with an energy distribution between cold and thermal. First measurements were performed at LENS using Cd decouplers; measurements were on-going on liquid natural ammonia to improve the scattering kernel and performance as a moderator for a pulsed source [219].

Similarly, liquid ethane was examined in a collaboration between CNEA-Bariloche and ISIS, in which measurements were performed on the Vesuvio instrument at the ISIS Facility, UK. Ethane has a broader liquid range (90–185 K) than methane (92–112 K), similar high proton density, and good low-frequency rotational dynamics (Figure 30). The results were encouraging, showing that liquid ethane at 100 K could give a higher production of neutrons than liquid methane at all neutron energies from thermal down to cold [204]. However, operational experience of liquid ethane at the ISIS Facility showed it broadened the pulse widths (Annex III).

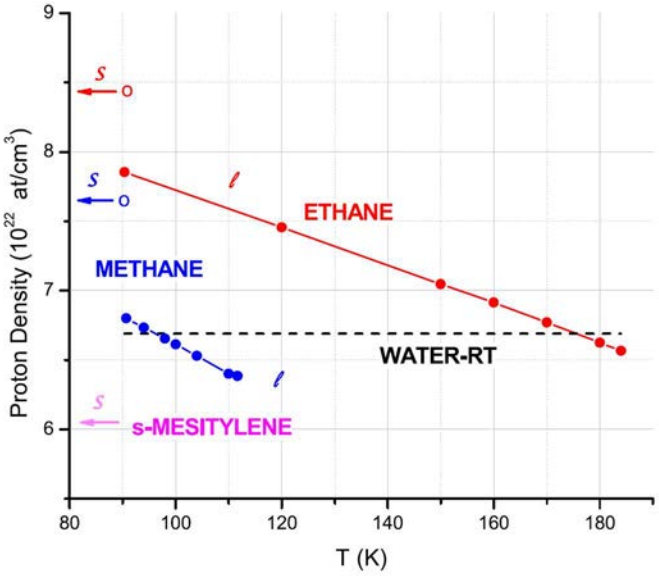

FIG. 30. Proton densities of ethane (liquid and solid), methane (liquid and solid), mesitylene compared to liquid water at room temperature as a reference by the authors of Ref. [204] is licensed under CC BY-4.0.

Although H_2O-ice is not an ideal material for a cold moderator, due to its low density of states in the appropriate part of the vibrational spectrum, it can be used as a 'cool' moderator, and it does offer the advantage of being a non-flammable, non-explosive material already present in reactors. The original cold moderator at the NIST NBSR reactor was based on mixed H/D ice (Table 2). A liquid-nitrogen cooled test system was being developed during the lifetime of the CRP at Bhabha Atomic Research Centre, India. Expected gains were approximately 7-fold for their wavelengths of interest compared to that emanating from a thermal moderator [220].

Another idea that stemmed from the investigation of Ref. [221] was to use the inherent anisotropy of some organic materials, such as liquid crystals, whose orientation can be controlled by an electric field. Within certain of these compounds, the steric hindrance encountered by hydrogen atoms, e.g., from aromatic rings, can result in certain 'easy' (softer) directions for vibration, which may yield preferred anisotropic moderation effects.

11.3. GEOMETRICAL OPTIMIZATION AND HETEROGENEOUS MODERATORS

Other gains from attempting to make the emission more anisotropic from a moderator assembly had been discussed by Ref. [222]. Concepts include:

a) Re-entrant and grooved moderator forms: Geometric gains have been used in the past (for non-*p*-hydrogen moderators), where emission is boosted from the centre of the moderator vessel in the direction of neutron beams or guides by 'dishing out' part of the moderator volume to access higher fluxes of fully moderated neutrons and boost emission in the preferred direction. A similar boost to that from re-entrant forms has previously been obtained from grooves on the exit side of moderator vessels;
b) Reflector–filters: As, in general, the cross sections of most materials increase with decreasing neutron energy, faster neutrons tend to leak out of most moderator materials preferentially ('spectral cooling'). This fast neutron background could be filtered, e.g., by using Be, which has a high coherent scattering cross section and low incoherent and absorption cross sections. The Bragg cut-off (the wavelength beyond which there is no Bragg scattering and the material becomes almost transparent to neutrons) in Be (Figure 2) gives the material its filtration capacity, and fast neutrons are returned to the moderator for further moderation;
c) Convoluted moderators: composites of moderator material and a semi-transparent emitter, whose presence may reduce back scattering and absorption from the whole system but also boosts the anisotropy in the layer direction by thermal and sub-thermal scattering processes;
d) Bi-spectral extraction where one instrument can view two moderators.

11.3.1. Grooved moderators

One of the questions raised was how to effectively get neutrons into a moderator. It had been recognised that the water thermal pre-moderator (Figure 10), common at spallation sources, may have just as much contribution as a back-reflector of neutrons that are reflected from the surface of the cold moderator [223]. Grooves in moderators on the 'cold' side have long been known to improve the flux escaping from the moderator volume. More recently, it had been postulated that similar re-entrant forms on the 'entrance' side of the moderator may enable similar gains. The effect of grooves on a model polyethylene (PE) moderator was examined at the NEUTRA radiography facility at SINQ, PSI, Switzerland using a thermalized neutron beam [223–225]. Measurements were performed on towers of 20 mm PE cubes as a function of angle to an incident beam with a variety of modifications, including none (solid PE), a through-penetrating hole, and a variety of grooves (Figure 31). The results show that there was a slightly larger effect for 'entry grooves' (i.e., grooves facing the primary neutron source) than for 'exit grooves', and this held true for neutrons emitted at all angles from the cube. However, the effect was not as strong as had been hoped, in the few % range [223–225].

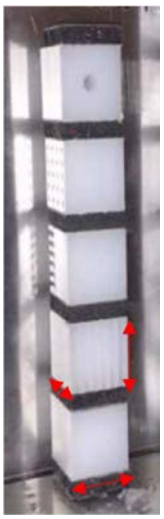

FIG. 31. Cubes of grooved PE moderators of 20 mm dimension (red arrows) used to test the effectiveness of 'entry' vs. 'exit' grooves (courtesy of K. Thomsen, PSI).

11.3.2. Reflector–filters

The world's first reflector–filter, made from polycrystalline Be and installed at the LANSCE facility, Los Alamos, USA, gave gains of more than two-fold for neutrons with $\lambda > 4$ Å ($E < 5$ meV), while reducing the undesirable fast neutrons by four-fold [226]. In a polycrystalline reflector–filter, the Bragg edge cut-off is independent of wavevector direction, providing strong quasi-isotopic scattering for $\lambda < 4$ Å, and almost none for $\lambda > 4$ Å. A full description of this cold Be reflector–filter as well as the modern configuration of the target–moderator–reflector system has been given in Ref. [227]. While the system produced longer tails for neutrons above the Be cut-off, due to the scattering action of the Be filter and the moderation properties of Be itself, the emission time from such a system was unaffected [228].

11.3.3. Convoluted moderators

At Necsa, South Africa, a convoluted moderator consisting of Si wafers and PE was examined [221], the aim being to boost directional emission for a small CANS [14]. The facility used a Li target with its van de Graaff accelerator with proton energies a little over the threshold for neutron production to generate epithermal neutrons with a forward bias in their angular emission from the target towards the moderator. A significant boost in the forward direction was observed from the convoluted moderator compared to that simulated from MCNPX, which at the time did not incorporate the ability to model anisotropic effects. This study also emphasized that more nuclear data is required to accurately model the behaviour of even common materials such as Si and PE across a wide neutron-energy range, to be able to take into account crystalline anisotropy (see Section 11.4.1).

11.3.4. Bi-spectral extraction

Bi-spectral extraction has been a theme examined in recent years: by placing two moderators (thermal and cold) side-by-side, it is possible that one instrument can view two different moderator sources. Mirrors that have total or high external reflection for cold neutrons yet high transmission for thermal neutrons are one way of utilizing such a source: the thermal moderator can be viewed face-on by the guide (through the mirror), while the cold source is viewed after bouncing from the mirror sections.

While a polycrystalline Be reflector–filter (Section 11.3.2) strongly reduces the proportion of unwanted 1 MeV neutrons, it also removes intermediate neutrons with energies down towards 1 eV, which for some experiments are not background, but useful [226]. Reference [229] had earlier reported investigations of ^{208}Pb as a reflector–filter for the purposes of bi-spectral extraction (i.e., both cold and thermal neutrons), and it is further described in Ref. [107]. Unlike Be, ^{208}Pb itself has essentially no moderating effect and, although it is not as efficient a reflector as Be either, it does not suppress the useful neutrons beyond the Be cut-off ($\lambda < 4$ Å). And, as it is a 'double-magic-number' nuclide, it has even lower neutron absorption than Be.

Another approach is to use a single-crystal Be reflector–filter, which encounters the diffraction condition for far fewer neutrons than a polycrystalline filter. The total cross section for such a single-crystal reflector–filter not in the diffraction condition is then dominated by inelastic and absorption cross sections. Transmission in the 'useful' range $\lambda \sim 1$–4 Å, immediately above the Bragg edge, is expected to be boosted, but the system preserves its effectiveness for strong rejection for neutrons with $\lambda < 0.5$ Å [228]. This concept was tested at the LENS facility, University of Indiana, USA during the CRP: although Be was not available, single-crystal and

polycrystalline corundum were tested within a PE moderator. The single-crystal reflector–filter did better in preserving the intermediate energy 'useful' neutrons [228].

The pelletized moderator system at the IRR-2M reactor, Dubna, Russian Federation, is also bi-spectral, combining a grooved water moderator for thermal neutrons with the pelletized cold moderator system [230]. This holds some advantages for measurements of texture of natural materials [231], where the gains at long wavelengths are realized without a great loss in the thermal spectrum. The efficacy of this bi-spectral scheme has also been reviewed for its benefits for polarized reflectometry, where a boost by a factor of ~10-fold in the cold spectrum was reported. Developments in the splitting of the beam after the moderator and the production of microbeams were also reported [232].

11.4. SCATTERING KERNELS AND TRANSPORT CODES

Several improvements in this area have occurred in recent years, including upgrading some of the neutron transport codes to better handle mesoscopic neutron interactions at thermal and lower neutron energies, improvements in interfacing between codes, and the developments of better scattering kernels and nuclear data.

11.4.1. Mesoscale effects at and below thermal neutron energies

At the time during which the CRP was running, the major neutron transport codes, such as Geant4 and MCNPX, did not handle the low-energy interactions such as reflection, refraction, and diffraction that are typical of low-energy neutrons (and the subject of the field of neutron scattering itself). One improvement required to model the reflector–filter mentioned above was to add coherent scattering to MCNPX [233], and the improvements were benchmarked against measurements of the Si–PE convoluted moderator at LENS. Improved modelling resulted from new scattering kernels collected for sapphire (corundum) and silicon in support of their use in convoluted moderators and filters, and new validated library entries for ENDF and ACE resulted. Recent developments have included interactions with mosaic single crystals and polycrystals in thermal neutron transport: e.g., NCrystal [234] and NJOY+NCrystal [235].

Another extension of 'neutron scattering' into the Monte Carlo transport codes has been to include small angle scattering effects, using an analytical model for hard spheres as well as user supplied data [236]. Initial validation testing demonstrated transmission and reflection properties consistent with expectations for small angle neutron scattering, transmission, and reflectometer geometries. Nanodiamonds look particularly promising for very cold neutrons where reflection is possible at almost all angles (see Section 11.5).

The importance of a global optimization of neutron scattering systems from the primary source through to the detectors has long been understood, especially given the cost of neutron scattering centres. There are several Monte Carlo codes, each with different strengths; e.g., for neutron transport (e.g., MCNP) and instrument optimisation (e.g., McStas), detectors and shielding (e.g., Geant4). Another major development during this period was that of an interface or intermediary: the binary Monte Carlo Particle List (MCPL) event-file format stores information about the particles, which acts as a lingua franca between many of these codes [237–238]. 'Hooks' were developed for the codes Geant4, McStas, MCNP, PHITS and McXtrace. Another important development in system modelling was the development of CombLayer, which allows the generation of parametric models of components and entire neutron scattering facilities [239–240].

11.4.2. Scattering kernels and nuclear data for moderator materials

A new treatment of the scattering from liquids involving the use of molecular dynamics was developed [241] to determine the frequency spectra of H, D, and O in water, and to generate kernels, from which double differential and integral cross sections were calculated. Later, *Q*-dependent random jump diffusion in liquids [1–243] was incorporated into the modelling and subsequently included in the LEAPR module[26] of the nuclear data processing code, NJOY[27]. While the model was developed for light water moderators, due to the abundance of data, this development can also be applied to any liquid cold moderator in which there is diffusional translational motion. Improvements were also made in the description of heavy water moderators in the temperature range of 40–70 °C that fixed an anomaly in the earlier ENDF entry [243]. The 'correctness' of this improvement was verified by new measurements at LENS [244] (Figure 32).

Improvements were made to the description of existing cold moderator materials by the group at CNEA-Bariloche, Argentina, including liquid hydrogen and liquid deuterium [245–246]. Most of the developments regarding thermal and cold moderator materials as well as filters have been now contributed to nuclear data libraries: the ENDF/B-VIII.0 library [103] and JEFF 3.3 [247].

11.5. HIGH ALBEDO MATERIALS

The possibilities regarding very cold and ultracold neutron sources for the ESS and SNS have been discussed [248–249]. For cold to ultracold neutrons, materials with a high albedo for long wavelength neutrons are required as they provide another way of boosting extracted fluxes. Nesvizhevsky had shown that nanodiamonds with a radius of ~5 nm would have near perfect reflection at all angles for neutrons with $\lambda \gtrsim 10$–20 Å, and specular reflection for $\lambda \lesssim 5$ Å [250]. The CRP was supplied with detonation nanodiamonds by Danish Technical University. Another supply, produced using laser synthesis, was commercially available. Nanodiamond samples were measured on the VISION instrument at SNS, Oak Ridge National Laboratory, USA to measure the vibrational excitation spectrum. Transmission measurements were made to determine total scattering at J-PARC [251]. Small angle neutron and X-ray scattering were performed at ANSTO in Australia [252].

To move from a material to a device, it will need to be possible to form nanodiamonds. Pressed plates were developed at J-PARC, which brought this material closer to use as a coating for a very cold neutron source. It was shown that the total scattering cross section of 5 nm nanodiamonds is about two orders of magnitude greater than that of graphite for neutrons of energy 0.2 meV, that there was increased forward scattering at low energies, and that that scattering was essentially elastic [251]. This elastically dominated signal was also seen at ANSTO [252]; this is important in their proposed use as cold/very cold reflector materials, as inelastic scattering would potentially 'up-scatter' neutrons. In general, inelastic scattering of neutrons with energies typical of CNSs was found to be negligible, but at high temperatures the inelastic spectra have features due to the presence of phonons from the nanodiamond core and the outer shells [252]. More recently, measurements have been made of the total scattering from detonation nanodiamonds and their efficacy as a means of extracting cold neutrons from a *p*-hydrogen CNS on a CANS examined [253].

[26] LEAPR: https://docs.njoy21.io/projects/tnsfd/en/latest/LEAPR/index.html.
[27] NJOY: http://www.njoy21.io/.

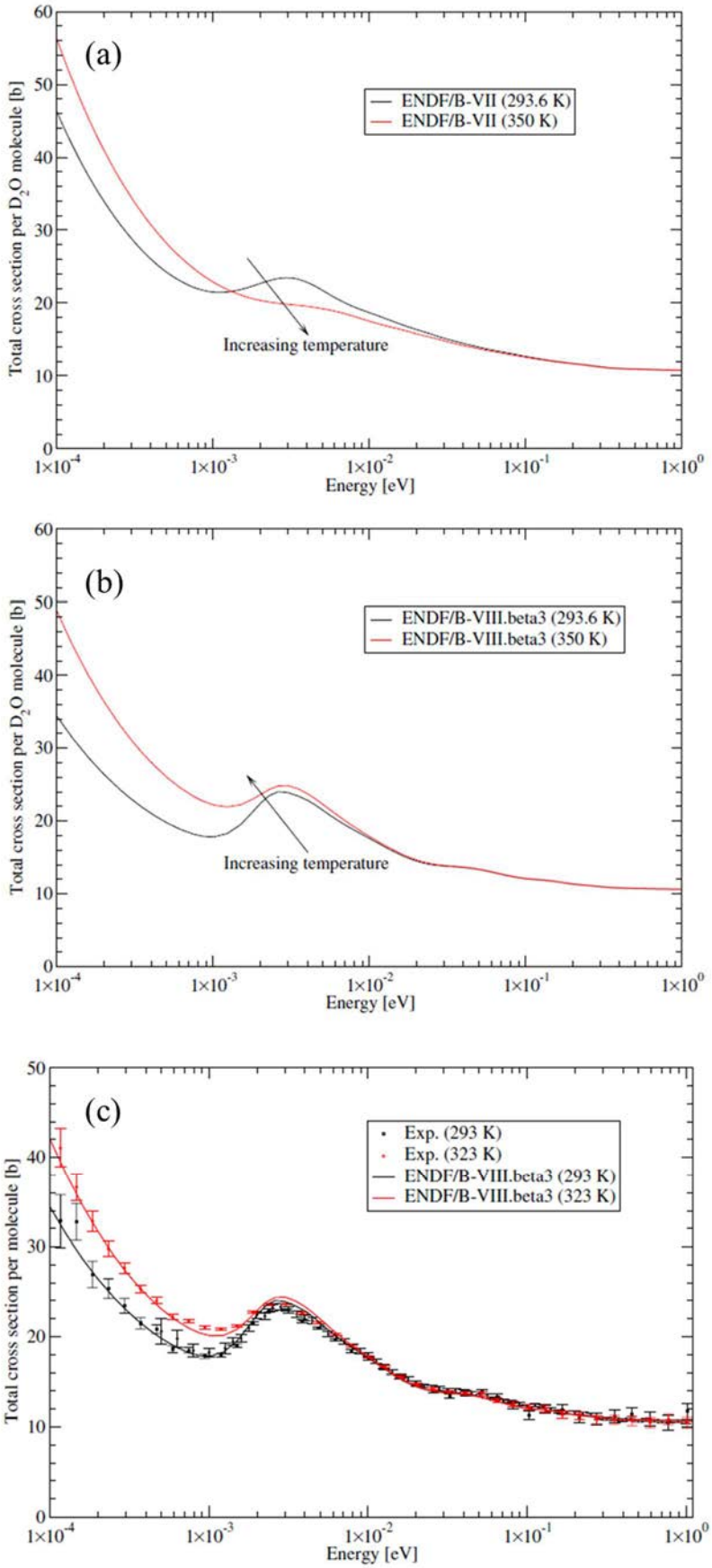

FIG. 32. (a) Original description of heavy water in the ENDF showing an anomalous decrease in cross section with increasing temperature (b) the modified model using the new description with jump diffusion with the expected thermal behaviour, (c) validation of the new model with measurements performed at LENS. This figure by the authors of Ref. [243] is licensed under CC BY-4.0.

One of the issues with nanodiamonds is surface contamination, in particular by hydrocarbons; this requires addressing before nanodiamonds can be deployed in mainstream use. Nanodiamonds typically consist of a true nanodiamond sp^3-bonded core surrounded by an envelope of less crystalline material. Small angle scattering (both of neutrons and X-rays) was used by groups at BRR, J-PARC, ANSTO, and ESS to characterize the size and structure of the nanodiamond particles. ANSTO's small angle neutron scattering measurements showed that the nanodiamonds approximated a rod shape [252]; small angle neutron and X-ray scattering measurements of nanodiamonds in a variety of solvents showed that the average radius was slightly less than 2–3 nm but that they formed clusters of 100–200 nm. A scattering kernel for diamond has since been developed by Granada and co-workers [254].

The presence of ^{1}H in nanodiamonds is the major contribution to the loss of neutrons, via absorption. Removal of adsorbed water by sample heating was found to suppress some of the inelastic scattering. In general, the removal of ^{1}H bound to carbon in the outer layers proved difficult. ANSTO attempted to deuterate some of these organic contaminants by a variety of methods and were successful, by using NaOD and Al at 250 °C under high pressure, in replacing half of the OH- or NH-groups. Fluorination has been proposed as a solution to remove hydrogen [255]. Reference [255] discuss the possibility that fluorinated nanodiamonds may help to fill the 'reflectivity gap' in that part of the cold neutron spectrum that lies between graphite and existing nanodiamonds (i.e., ca. 200–700 m/s | 19.78–5.65 Å | 0.21–2.55 meV). However, Granada and co-workers [254] have suggested that MgH_2 may represent a good candidate as a high-albedo directional reflector in this energy regime (Figure 33).

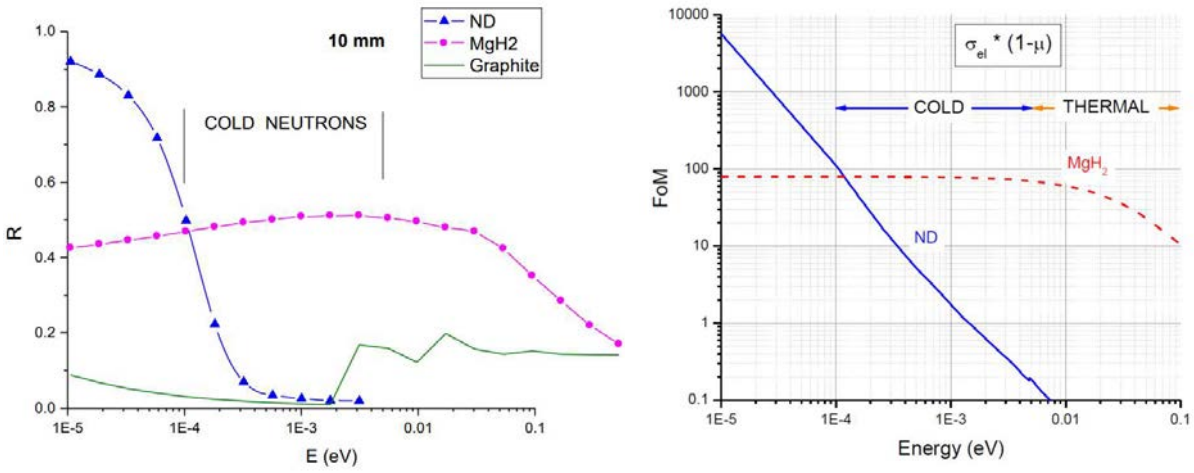

FIG. 33. a) Comparison of reflectivity of nanodiamonds (ND), graphite, and MgH_2, showing MgH_2 may help fill the 'reflectivity gap'. b) Figure of merit (the elastic cross section corrected for (1-μ), where μ is the scattering cosine) comparing nanodiamonds and MgH_2 as neutron reflectors. This figure by the authors of Ref. [254] is licensed under CC BY-4.0.

Appendix I.

OUTLINE OF A QUALITY ASSURANCE DOCUMENT FOR MANUFACTURING

A typical document package may contain the following documents and be reviewed before manufacturing.

- Design specification;
- Load history report;
- Design description document;
- Fluid dynamic calculation report;
- Structural mechanic calculation report;
- Hazard analyses;
- Bill of materials;
- Part-, assembly-, welding- drawings;
- Welding process qualification report;
- Welding process specifications;
- Cleaning specification;
- Inspections plans;
- Certification of the company's authorization for heat treatment;
- The non-destructive testing company's certificate of accreditation and its extent;
- The non-destructive testing personnel's certificate of examination;
- Review of authorization for coupling installation/Qualification of personnel;
- Certification of the company's authorization for joining materials;
- Certification of welders;
- Non-destructive testing procedures;
- Program for pressure and tightness testing;
- Tolerances and uncertainties;
- Positional tolerances;
- Contingency requirements.

Appendix II.

OUTLINE OF A QUALITY ASSURANCE INSPECTION PLAN

A typical quality assurance inspection plan may contain these typical elements:

- Inspection of materials;
  - Material certificate;
  - Mechanical testing of material;
  - Marking and identification;
  - Material tracking;
  - Heat treatment;
  - Visual inspection;
  - Dimensional inspection;
- Inspection of welding;
  - Welding procedure qualification ;
  - Welding process specification;
  - Welder and welding operator qualification;
  - Test of weld filler material;
  - Visual inspection of welds;
  - Dimensional inspection of welds;
- Inspection of pipe bending;
- Inspection of installation of couplings;
- Inspection of cleanliness;
- Non-destructive tests;
  - Visual inspection;
  - Dimensional inspection;
  - Pressure test;
  - Helium leak test;
  - Quench test;
  - X-ray inspection;
  - Dry penetration test.

Appendix III.

TRITIUM ACTIVITY AND RADIOLOGICAL SAFETY IN DEUTERIUM BASED COLD NEUTRON SOURCES

The magnitude of a potential radiological hazard primarily depends on the source strength (Ci)[28] of the radioisotope involved. In this case, the tritium production rate is proportional to the deuterium inventory contained within the CNS shell and the thermal neutron flux. The expected tritium source strength for such cases ranges from several to a few tens of Ci per litre, depending on the thermal flux to which CNS moderator shell is exposed and the irradiation time (proportional to reactor operation time). The tritium activity attains saturation level over a time scale almost equal to the life of a reactor since its half-life is 12.32 years. The thermal flux at the CNS shell generally ranges from ~10^{13} to 10^{15} $cm^{-2} \cdot s^{-1}$ and the deuterium moderator volume is typically 20–25 litres [256–257].

The radiological hazards of a liquid deuterium CNS have two components:

(a) Dose due to tritium build-up (β radiation). If deuterium is used as the moderator, the build-up of tritium in the inventory may be significant over many years of operation. Tritium decays with a half-life of 12.32 years by emitting a β particle with an end point energy of 18 keV. The literature on tritium related radiological safety issues in case of deuterium-based CNS is rather scant. The reason may be that worldwide, there are fewer deuterium-based CNSs than other CNSs and hence the operational experience is limited. However, experience in dealing with tritium activity is available in plenty in case of heavy water moderated reactors [258]. A strategy for the management and eventual disposal of the deuterium inventory needs to take tritium build-up into account. Tritium, being a low energy β particle emitter only gives an internal dose when it is inhaled but can cause some damage on skin in case of large external exposure. It does not have any other significant hazard in terms of external dose. Therefore, as far as tritium activity is concerned in the replacement and maintenance of a CNS, it can be tackled relatively easily by using masks supplied with a fresh air line to avoid inhalation. Special plastic suits can help to protect against skin damage. The γ field in the working area is a major concern and has to be addressed appropriately.
In a deuterium moderated CNS, tritium activity is localised in space, and is confined at 20 K in triple containment. These conditions strongly reduce the possibility of radioactive leaks. Being a low energy β emitter, tritium has relatively low radiological impact. But as it can become an airborne activity that can enter the human body, tritium handling is an important radiological safety issue. This has to be addressed appropriately during normal operation as well as accident conditions. An effective tritium leakage detection system needs to be installed for monitoring the tritium activity in the vicinity of the CNS assembly. Periodic air sample analysis needs to be carried out. A site-specific emergency plan needs to be there and in case of accidental release of activity, an approved ‘Emergency Operating Procedure’ has to be followed;

(b) Dose due to neutron activation of structural components of the CNS (γ radiation). Cobalt impurities in structural materials is one of the causes. The dose rates due to β particles during repair or replacement of a CNS are expected to be smaller than the γ dose rate due to the activated CNS structural materials. The high dose rate due to this activation and other sources determine the specifications of a suitable tritium monitor and its sensitivity: the response of the tritium detector cannot be affected.

[28] 1 Ci = 3.7×10^{10} Bq.

In heavy water moderated CANDU reactors, after 10 years of operation time, in a core average neutron flux of ~10^{14} $cm^{-2} \cdot s^{-1}$, the specific activity of tritium in the moderator is 3–20 Ci/litre [259]. The same approach can be followed in the calculation of the source strength in the case of a deuterium CNS since everything is the same except the density of the moderating material. Let us assume that the CNS moderating shell is exposed to a thermal neutron fluence of ~10^{14} cm^{-2} in the reactor reflector region. The density of liquid D_2 at 20 K temperature is 162 kg/m^3 [256–257]; this will result in a tritium activity 1.35 times higher than the activity in the moderator of the CANDU reactor mentioned above. Hence, for a deuterium CNS, the maximum value of tritium specific activity can be taken as ~27 Ci/l.

III.1. POSSIBILITY OF LEAKAGES

As a reference, we can take the example of tritium leakage in a heavy water moderated reactor. In a 220 MWe heavy water moderated CANDU reactor, in normal operation, the background air borne tritium activity is less than 1 DAC (Derived Activity Concentration) in the reactor containment building [259]. The leakage in the evapouration route is proportional to the total amount and spatial distribution of the deuterium inventory in the system. The deuterium inventory in a CNS system is a few tens of litres, which is much smaller than the heavy water inventory (several hundred tonnes) in a heavy water moderated reactor. Though the specific activity of tritium in a CNS is marginally higher than that in the heavy water moderator of a power reactor, the total activity in the CNS is much smaller. Also, the deuterium/tritium inventory is much more localised in the CNS system than in a heavy water moderated reactor, so that the probability of leakage of tritium from the CNS system via evapouration is smaller. Further, deuterium in the CNS shell is in the liquid state when operational at 20 K, which limits the mobility and evapouration rate [260]. However, this advantage is removed when the CNS warms up. Finally, as the deuterium moderator in the CNS system is held in triple containment (Section 6.3), the possibility of tritium leakage is further reduced. Nevertheless, appropriate precautions and safety practices need to be followed. For detecting tritium leakage, suitable tritium detection systems have to be installed in and around the CNS system. The IAEA Publication TRS 324 gives an overview of safe handling of tritium [261].

III.2. PRECAUTIONS DURING NORMAL OPERATION

As we have seen in the preceding section, there is a very low but finite probability of tritium leakage. Therefore, periodic monitoring of the He cover gas of a CNS is required. The vapour around the cryogenic system can have traces of tritium. The condensate sample in the cooling gas circuit, if it is available, can be collected for analysis. The condensate sample from ambient air may be collected by the ‘cold finger method’ at regular intervals. The tritium activity in these samples may be measured using a liquid scintillator counter. Temperature and pressure monitoring is performed at all key points in the system. Apart from the regular checks, additional sample analysis needs to be done if parameters deviate from those expected for normal operation. Generally, any tritium activity released exits via the gas stacks. However, guidelines set by the respective regulatory authority have to be followed while discharging radioactivity through stacks. Alternatively, it can be trapped using a vapour recovery system in which vapours are condensed and removed; such a system may be connected to the CNS assembly. The design of a CNS ought to be such that it can be considered effectively outside the reactor system. In addition to the precautions mentioned here, the inventory of deuterium may be replaced, say, after 10 years of operation, or once it reaches a certain level of activity. In the context of fire safety (Section 6.3), as there is the possibility of forming an explosive

mixture with oxygen, similar safety measures for both hydrogen and deuterium CNS systems are required.

III.3. ACCIDENTAL RELEASE

The possibility of tritium release, other than under normal operation, is classified as accidental release. For example, if temperature control of the deuterium circuit fails, deuterium may freeze and block the circuit leading to a pressure build up in the moderator shell, which may eventually burst. Another possibility is that the outflowing boiling deuterium creates strain on the confinement boundary and a high overpressure in the cryo-vacuum, which may lead to release of tritium. To negate the possibilities of such accidents, the deuterium circuit and the vacuum liner are set to such a high bursting pressure that the deuterium/tritium normally stays confined in the installation. Such an accident needs to be studied by simulations and the system needs to be designed and commissioned to withstand anticipated pressure build up in accident conditions (Sections 4.5, 5–8). The vacuum tubes need to be dimensioned in order to cope with the quantity of evapourated deuterium.

As a safety design feature, a ventilation duct may be installed in the vicinity of the CNS system, so that in case of an accidental release, the released activity will be ventilated directly outside the system. It will ensure that there is no activity build-up in the vicinity of the CNS system.

III.4. TRITIUM MONITORING AND DETECTION SYSTEMS

A compensated gamma ion chamber is generally used to detect the airborne tritium activity in the reactor containment of a heavy water moderated reactor. Permitted background airborne concentrations in a reactor hall under normal operating conditions are lower than 1 DAC [260], so the concentration level required to activate the alarm system is set to 1 DAC. The minimum detection activity (MDA) of the ion chamber is generally 0.1 DAC. A similar detector may be employed in the vicinity of the CNS assembly. However, as the total tritium activity in a deuterium CNS is much smaller than in the moderator of a heavy water reactor, a lower value, maybe a fraction of a DAC, may be set as the threshold value for activating the alarm in tritium detector around a CNS. The sensitivity of the gamma compensated ion chamber used for a CNS ought to be much higher than that used in a reactor, but there may be a restriction on size (active volume) of the detector due to the limited space available in the vicinity of the CNS: these requirements (greater sensitivity, smaller size) can be in opposition and a compromise may be required. Increasing the air pressure inside the ion chamber may help to increase the sensitivity.

The tritium detection system may be attached to the cooling gas circuit of the cryogenic system, as the cooling gas is in the closest contact with the deuterium filled moderator shell. Even a very small amount of tritium leakage may be detected by employing such a system. In addition to online monitoring, high sensitivity HTO-in-air measurements may also be made periodically by cooling the air and collecting the condensate sample.

Proportional counters are used to monitor very low concentrations of tritium, below the range of ionization chamber instruments, e.g., as low as 500 Bq/m^3. Sensitivity of 0.01 Ci/m^3 is achievable with a counting time of about one minute [258]. Proportional counters are of higher cost, more complex and require a counting gas. But using a tritium detector with a lower MDA may be problematic if the detector is sensitive to gamma radiation and placed in a high background area. In that case, a proportional counter has an advantage, that it has an inherent ability to discriminate against other unwanted penetrating radiations.

Plastic scintillator based advanced tritium detectors which can work with a multi-channel analyser are also being designed. The MDA is claimed to be ~30 kBq/m^3 [262]. Unlike the gas-filled type, the background counting rate of the scintillation-based detector is relatively stable to temperature and humidity in the surrounding area.

III.5. EMERGENCY RESPONSE

It is important to examine the history of accidents that have occurred in tritium facilities and to consider foreseeable unplanned events in order to minimize or mitigate their effects or to prevent their taking place at all. In case of significant leakage, after tritium monitors alarm, the local area first needs to be evacuated and the situation can then be further investigated. The facility has to have a site-specific emergency plan. An approved emergency operating procedure needs to be in place and to include an area evacuation procedure, based upon tritium airborne concentration / alarm level set of the tritium monitors. Personnel required to work for normalizing the situation have to use suitable protective gears like PVC suits, fresh air line respirators etc. to avoid any internal exposure due to inhalation and skin absorption of tritium. Those who have accidently inhaled tritiated vapour have to be subjected to bioassay monitoring for dose estimation and corrective actions. Re-entry in the area needs to be planned only after the airborne tritium level has returned to normal values. All radiological workers at the site have to be familiar with all aspects of this plan. In addition, job assignments involving radiological hazards need to be covered by procedures and work permits that include steps for emergency situations that may arise during the course of the work. Radiological workers need to be familiar with these procedures or be accompanied by a radiological control technician to provide guidance in case of an emergency. When an accident does occur, requirements for reporting accidents have to be followed.

III.6. REPLACEMENT AND MAINTENANCE

During the design lifetime of the facility, there are instances, when the CNS requires replacement or upgradation of its components. Apart from this, some routine maintenance jobs may be there on a periodic basis (e.g., every ten years). Minimising radiological impact during upgrades/maintenance job needs to be one of the design objectives. Material choice and mechanical connection provisions needs to be considered in the original design accordingly (Section 4.5). And finally, there needs to be a strategy for the management and eventual disposal of the deuterium and tritium inventory.

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Annex I.

RADIOALYSIS AND STORED ENERGY RELEASE IN A MESITYLENE MODERATOR CHAMBER

Radiolysis of solid moderating materials could cause explosive gas production in the moderator chamber. For example: Mesitylene decomposes under radiation, the primary products of radiolysis in this case are hydrogen, methane and C_2H_4. If the radiolysis proceeds for a long period of time without recombination, the energy in the radiolysis products could be released in a short time upon warm-up of the moderator. The spontaneous release of this stored energy could cause a rapid rise in the moderator temperature. The temperature surge could accelerate a change in state from solid to liquid or gas causing an increase in the pressure for moderating chamber. This sudden pressure increase for the moderating material could be dangerous.

The sources of the possible energy release depend on the material used in the moderator and their behaviour under irradiation. The description below is based around the Texas Cold Neutron Source (TCNS). The potential energy release mechanisms are:

- Hydrogen–oxygen reaction;
- Hydrogen–hydrogen recombination;
- Irradiation damage caused by collisions of fast neutrons;
- Ozone decomposition.

The sources of these phenomena are radiolysis of the moderating material, release of stored chemical energy upon warm-up from the moderating material and the moderator chamber, and the reaction of the ozone produced under irradiation with other agents. These energy release mechanisms (except ozone decomposition) and their potential impacts on the safety of the TCNS system are discussed in this publication.

Radiolysis of moderating materials could cause explosions in the moderator chamber due to hydrogen–oxygen reactions and ozone decomposition (known to be a non-issue) or reaction with other agents. The possibility of an explosion in the moderator chamber increases drastically if a change of state of the moderating material (i.e., from solid or liquid to gas) causes an increase in pressure. These problems are very common with customarily used moderators, such as hydrogen and methane. To mitigate potential problems associated with these moderating materials, mesitylene (1,3,5-trimethylbenzene) was chosen as the moderator.

Mesitylene is a hydrocarbon, and it has been shown by Utsuro et al. [I-l] to be an effective moderator. Mesitylene is a liquid at room temperature and, therefore, large increases in pressure due to a change of state will not occur. Mesitylene freezes at 220 K and boils at 438 K. It can be left free-standing at room or cold temperatures and will not catch fire due to its high ignition point, 823 K [I-2]. Mesitylene is a toxic benzene derivative and inhalation of as little as 10 ppm could affect the central nervous system [I-3]. Therefore, direct exposure to mesitylene of persons working in the vicinity has to be avoided. Exposure to mesitylene is prevented in the TCNS by handling the flow of mesitylene with a closed loop system. Also, a gas absorber connected to a relief valve will collect escaping gases in case of an abnormal pressure build-up of the mesitylene closed loop system.

Mesitylene decomposes under radiation at the rate of less than 0.013% per fast neutron fluence of 1.4×10^{16} cm^{-2} [I-4–I-5]. The primary products of radiolysis are hydrogen (~91%), methane (6.9%), and C_2H_4 (1.38%) [I-6]. By using data reported by Utsuro et al. [I-4] the production rate

of hydrogen was calculated for a TCNS moderator chamber having a volume of 88 cm^3. With an estimated fast neutron flux of 5×10^{11} $cm^{-2} \cdot s^{-1}$ the decomposition rate is 1.36×10^{-3} g/h. At this rate, 0.098 g of hydrogen (~1 litre at NTP) would accumulate in the moderator chamber during a continuous reactor operating time of 72 hours. With the assumption that 5% of the moderator chamber volume is filled with air, the amount of oxygen in the moderator chamber would be 3.57×10^{-5} mole. If all the hydrogen produced by radiolysis is released from the moderator into the chamber, the energy released from a hydrogen–oxygen reaction would be 20 J ($H_2 + ½\ O_2 \rightarrow H_2O + 285.5$ kJ). If this energy is released to the gas in the void in the moderator chamber, the pressure would increase to 50 atm. The void was taken to be 4 cm^3, assuming frozen mesitylene blocks the upper fill line. Under the assumption that the upper fill line is not blocked, the pressure increases to only 2 atm. The calculated internal bursting pressure of the moderator chamber is ~84 atm. In either case, the moderator chamber will not rupture in the event of a hydrogen–oxygen reaction. However, such a hydrogen–oxygen reaction is not likely to occur. The volume not occupied by mesitylene in the closed-loop system is kept under a He atmosphere. Also, a significant amount of the oxygen from air left in the system or from impurity in the He supply is diluted by liquid or solid mesitylene. Due to the very limited amount of oxygen in the system, no significant amount of ozone production is expected in the moderator chamber.

Since the mobility of radiolysis products is greatly reduced in the cooled moderator, these products are only released on warming. If the radiolysis proceeds for a long period of time without recombination, the energy in the radiolysis products could be released within a short time upon warm-up of the moderator. The spontaneous release of this stored energy could cause a rapid rise in the moderator temperature. The temperature surge could accelerate a change in state from solid to liquid or gas causing an increase in the pressure for moderating chamber. This sudden pressure increase for the moderating material could be dangerous. Therefore, an evaluation was made to demonstrate the effect of the stored energy in the moderating chamber for the TCNS.

The heat release could originate from radiation damage in the Al chamber and the stored energy release from the radiolysis products of the mesitylene. Radiation damage caused by the collisions of fast neutrons with the nuclei or atoms in the Al crystals will result in atomic displacement and create vacancies and interstitials (Frenkel pairs). Radiation damage energy accumulations in aluminium were measured at the Intense Pulsed Neutron Source (IPNS), Argonne National Laboratory by J. M. Carpenter for the IPNS methane-moderated cold neutron source [I-7]. They observed about 1.1 J/g energy release in the empty Al chamber when it was irradiated for one day at 21 K with a fast neutron flux of $\sim 5 \times 10^{12}$ $cm^{-2} \cdot s^{-1}$. When we assume the same rate of 1.1 J/g energy release for TCNS, the accumulated energy due to radiation damage in the Al chamber would be ~21 J for 72 hours of continuous irradiation. The released energy will be absorbed by solid or liquid mesitylene in the chamber. Therefore, the heat release due to the radiation damage in the Al chamber will not contribute significantly to any sudden temperature increase in the moderator.

The primary product of the radiolysis of mesitylene is hydrogen. By assuming data reported by Utsuro et al. [I-4], the hydrogen accumulated in the TCNS chamber during 72 hours of continuous irradiation at full power was calculated to be 0.098 g (~1 L at NTP). If all of this hydrogen recombines suddenly, it would release 10.7 kJ of energy ($H + H \rightarrow H_2 + 218$ kJ/mol). This calculation is based on the assumption that all the stored energy held by mesitylene that evolves after irradiation and warm up is stored as H, and that H accumulates until an $H + H \rightarrow H_2$ reaction occurs. Taking the worst-case situation that the upper fill line is blocked with solid mesitylene and all of the atomic H is in the 4 cm^3 void and recombines there instantaneously, the pressure in the moderator chamber would reach 7,000 atm. If the upper fill

line is not blocked with solid mesitylene, the pressure in the chamber could reach 200 atm. Although a relief valve is attached to the system, the sudden burst of pressure in either case would rupture the moderator chamber. This pressure would then be distributed to the total evacuated volume of 125 L, and the pressure in the system would increase from 0.00 to 0.84 atm. This sudden pressure increase in the evacuated region would not change the integrity of the vacuum jacket, which would contain the damage to the cold source system.

When the moderator chamber ruptures due to this sudden burst of pressure, some small pieces of materials may hit the vacuum jacket. This is a concern at the moderator region since this part of the TCNS is placed in the graphite reflector of the reactor. For the TCNS system, any projectile traveling toward the core region is contained by the 0.32 cm thick Al inner vacuum jacket, 7.62 cm thick Pb shield, 0.64 cm thick Al outside cover, and 0.71 cm thick Al beam tube. Projectiles traveling in the radial direction away from the beam port axis are contained again by a 0.32 cm thick Al inner vacuum jacket, 1.42 cm thick Pb shield, 0.32 cm thick Al outside cover jacket, and 0.71 cm thick Al beam tube. Any projectile which has an increment of 10.7 kJ kinetic energy will not be able to penetrate the 0.32 cm thick Al inner vacuum jacket.

The calculations related to heat release due to a hydrogen–oxygen reaction, hydrogen–hydrogen recombination, and radiation damage in the moderator chamber reflect a worst-case scenario. At most we may expect a rupture of the moderator chamber and/or fill lines which have been shown to be non-safety issues for the reactor. Any sudden release of sufficient energy to damage the reactor is not credible. The sudden pressure changes in the evacuated region including inadvertent leakage of the moderating material will result in the actuation of the electropneumatic gate valves and the vacuum region will be isolated.

I-1. CONCLUSION

The safety problems associated with commonly used moderators such as hydrogen, deuterium, or methane are eliminated for the TCNS by using mesitylene as a moderator. Hydrogen, deuterium, and methane are gaseous at room temperature, and possible sudden temperature changes may lead to a dangerous pressure build-up in the moderator chamber. Mesitylene is a liquid at room temperature and is not explosive. It is a hydrogenous material with nuclear properties comparable to hydrogen. The radiolysis of mesitylene and stored energy in the moderator chamber and mesitylene have been evaluated. It was concluded that even in worst-case scenarios there would be no safety issue related to any damage to the reactor components and reactor core. Under all of the above evaluations, it is concluded that no credible accident involving the TCNS could cause damage to either the reactor beam tube or reactor core nor cause releases of radioactivity in excess of the limits prescribed by 10 CFR 20 [I-8].

REFERENCES TO ANNEX I

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[I-5] VAN DINGENEN, W., Systematic study of some cold-neutron sources, Nucl. Instrum. Methods **16** (1962) 116.

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[I-7] CARPENTER, J.M., Thermally activated release of stored chemical energy in cryogenic media, Nature **330** (1987) 358–360.

[I-8] U.S. NUCLEAR REGULATORY COMMISSION, NRC Regulations Title 10, Code of Federal Regulations (10 CFR) Part 20—Standards for Protection Against Radiation, https://www.nrc.gov/reading-rm/doc-collections/cfr/index.html.

Annex II.

DEVELOPMENT OF A COLD NEUTRON SOURCE AND NEUTRON BEAM FACILITIES AT THE PENN STATE BREAZEALE REACTOR

The research applications at university research reactors can be enhanced by using subthermal neutrons—'cold neutrons'. The 'temperature' of a neutron beam can be reduced by passing it through a cold moderator. Cold neutrons have lower energies and larger wavelengths than thermal neutrons and can be reflected from some surfaces. They can be transported using neutron guides without the normal l/r^2 attenuation and be bent out of the line-of-sight paths followed by other radiations. In the past two decades, only two cold neutron beam facilities were developed at U.S. university research reactors, namely at Cornell University and the University of Texas at Austin.

The Cornell Cold Neutron Beam Facility (CNBF) included a moderator, a cryorefrigerator, Cu cold fingers, a neutron guide system, vacuum jackets, shielding, and various connecting and control lines [II-1–II-4]. The mesitylene (1,3,5-trimethylbenzene) moderator in the CNBF was cooled by a He cryorefrigerator via Cu cold fingers to maintain the moderator below 30 K at full power (500 kW) reactor operation. Cold neutrons from the mesitylene moderator were transported to an experimental facility using thirteen 1-m long natural-Ni coated neutron guide elements. The Texas Cold Neutron Source (TCNS) uses a mesitylene moderator that is cooled by a cryorefrigerator via a Ne thermosyphon [II-5–II-10]. The operation of the TCNS is based on a He cryorefrigerator, which liquefies Ne gas in a 3-m long thermosyphon. The thermosiphon cools and maintains the mesitylene moderator at ~30 K in a chamber. Neutrons stream through the mesitylene chamber where they are moderated. The cold neutrons are transported out of the biological shield of the reactor to a sample chamber location by a 6-m long curved neutron guide and an 80-cm long converging neutron guide. The design features, cooling and warm-up characteristics, and the performances of both CNBF and TCNS will be briefly discussed below.

An investigation of thermal and thermohydraulic characteristics of the cooling systems of both CNBF and TCNS was carried out in order to design and build a mesitylene based cold neutron source at the Penn State University, Breazeale Nuclear Reactor (PSBR) [II-11–II-16]. A third generation of mesitylene moderated university cold neutron source (CNS) is being built at the Penn State Breazeale Reactor (PSBR). The operation of the PSBR-CNS is based on a He cryorefrigerator and circulating He line. Circulating liquid-He cools and maintains the cold neutron moderator material (mesitylene) at ~15–20 K in a 10 cm diameter Al chamber located inside the D_2O tank of the PSBR. The cold neutrons coming from the mesitylene chamber are transported out of the biological shield of the reactor with three super-mirror neutron guides. New core–moderator assembly and new beam ports and design features of the PSBR-CNS are presented below.

II-1. UNIVERSITY RESEARCH REACTOR COLD NEUTRON BEAM FACILITIES IN THE USA

The two earlier CNS systems at university research reactors are briefly reviewed below.

II-1.1. Cornell Cold Neutron Beam Facility

The CNBF was located at one of the radial beam ports of the 500 kW TRIGA research reactor and adjacent beam floor area (Figure II-1a) [II-1–II-4]. (Cornell University administration

decided to close the Ward Center for Nuclear Sciences on June 2002, and hence Cornell reactor and the Ward Center for Nuclear Sciences are no longer available for the scientific community). The CNBF consisted of a cooled moderator, a cryorefrigerator, a Cu rod (cold finger), and neutron guide elements (Figure II-1b). The moderator was placed in a neutron beam port close to the reactor core. The moderator used in the Cornell cold neutron source was mesitylene. Because mesitylene freezes at 228 K and boils at 437 K, it is safer and much simpler to use than liquid hydrogen, D_2O ice, or solid methane, the more traditional cold-neutron-source moderators. The handling system for mesitylene does not need to withstand large or abrupt changes in pressure but has to be a closed system to avoid contaminating the mesitylene or releasing it, since it is slightly carcinogenic and toxic.

The CNBF moderator was contained in a thin-walled Al, right-circular cylinder of 7.5 cm diameter × 2.5 cm deep positioned inside a beam tube at the graphite reflector of the reactor. The moderator was cooled by conduction through a five-9's purity (99.999+%) 1.8 cm diameter × 216 cm long Cu rod. The Cu rod was connected to the second stage of a cryogenic refrigerator located outside the biological shield of the reactor. A Gifford-McMahon cycle Cryomech model GB04 He cryorefrigerator was used for cooling. The moderator chamber temperature varied from 11 K at 0.0 kW reactor power with an evacuated chamber to 28.5 K at 500 kW reactor power with a mesitylene-filled chamber. The neutron guide of the CNBF contained thirteen 1-m long elements. Each element was comprised of two parallel side plates of dimension: 8 cm high × 100 cm long × 1 cm thickness, separated top and bottom by epoxied, ground glass strips of dimensions 2 cm wide × 100 cm long × 1 cm thick. The cross-sectional view resembled a 'double bar H', with internal dimensions of 2 cm wide × 5 cm high. The four interior surfaces were coated with a 5 Å-thick evapourated layer of natural-Ni. The predicted thermal equivalent flux at the exit of the guides at 480 kW reactor power was about 4×10^6 $cm^{-2} \cdot s^{-1}$.

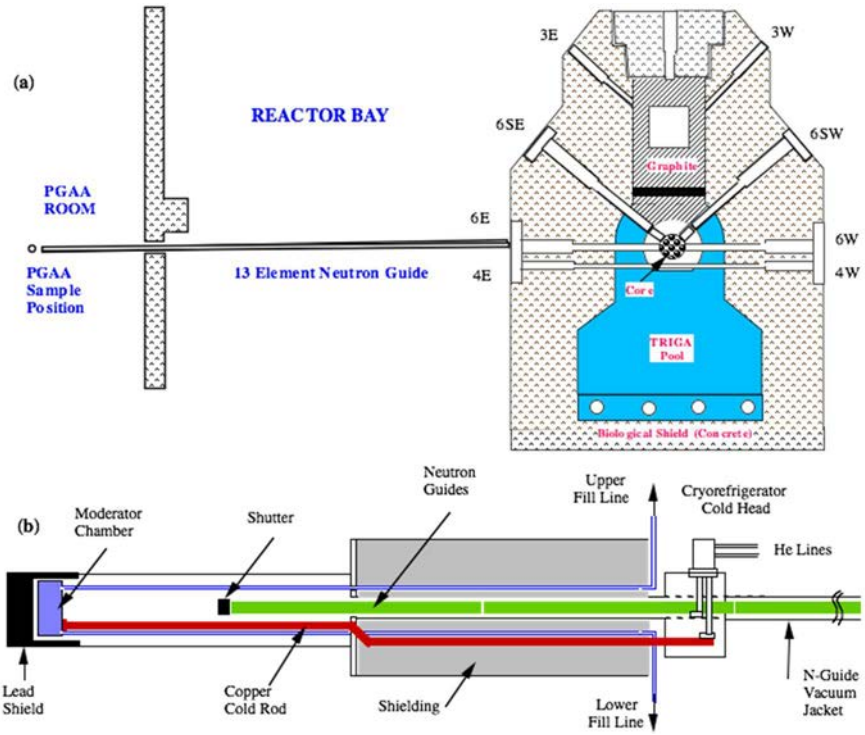

FIG. II-1. Schematic drawing of the Cornell Cold Neutron Beam Facility. (a) Plan view (b) Detail of the CNS (courtesy of K. Ünlü, PSBR).

II-1.2. Texas Cold Neutron Source

The operation of the TCNS is based on a He cryorefrigerator, which liquefies neon gas in a 3-m long thermosyphon [II-5–II-10]. The thermosyphon cools and maintains a cold neutron moderating material (mesitylene) at about 30 K in an Al chamber located inside the graphite reflector of the University of Texas at Austin 1000-kW research reactor. The cooling down and warming up trends of the TCNS is similar to that of the Cornell Cold Neutron Source. Neutrons streaming through the mesitylene chamber are moderated. The cold neutrons coming from the mesitylene chamber are transported out of the biological shield of the reactor to the PGAA sample chamber location by a 6-m long curved neutron guide and an 80-cm long converging neutron guide. Figure II-2 is a cross sectional view of the external components of the TCNS, curved guides and the UT-PGAA facility. The curved neutron guide is made up by three 2-m long sections, curved to a 300-m radius and divided into three vertical channels (5 × 0.45 cm) by 0.1-cm-thick walls. This array provides blocking of the straight-path background radiation components that stream through the guide. The TCNS curved neutron guide, with all reflecting surfaces coated by a 1000-Å ^{58}Ni layer, utilizes total reflection to transport neutrons without the normal $1/r^2$ intensity loss. The critical angle for total reflection of neutrons from ^{58}Ni is 0.12° per Å. The characteristic wavelength of the curved neutron guide is 2.7 Å, which corresponds to neutron energy of 11 meV.

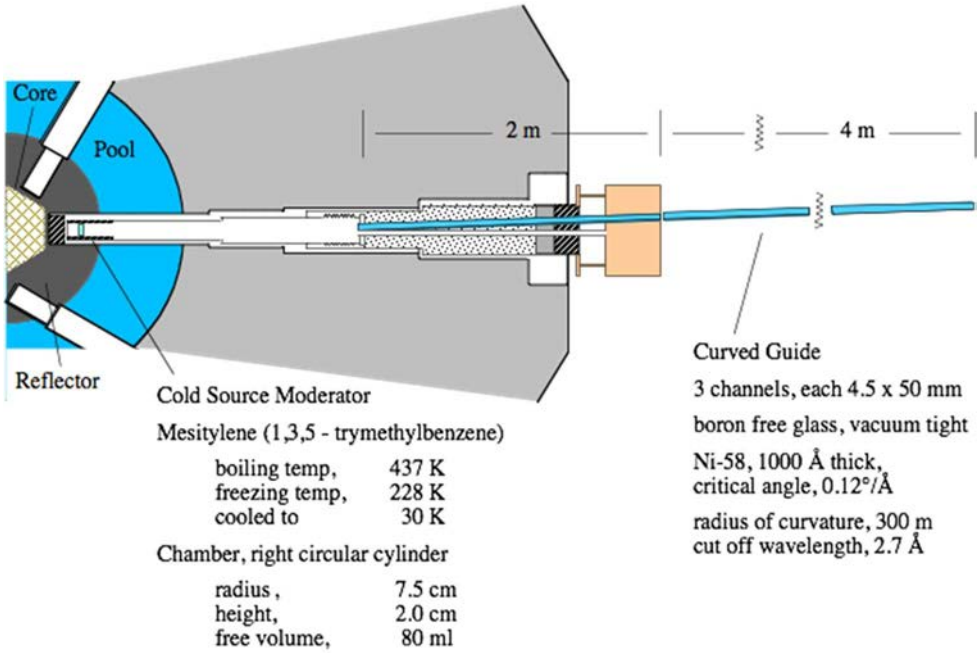

FIG. II-2. Cross-sectional view of the Texas Cold Neutron Source in the piercing beam port of the UT-TRIGA research reactor, showing the location of the 6 m long curved neutron guide (courtesy of K. Ünlü, PSBR).

II-2. PENN STATE BREAZEALE NUCLEAR REACTOR

The Penn State Breazeale Reactor (PSBR) at the Radiation Science and Engineering Center (RSEC) is a 1 MW TRIGA Mark III reactor with pulsing capabilities. The moveable core at PSBR has no fixed reflector and is located in a 24 ft deep pool with ~71,000 gallons of demineralized water. A variety of dry tubes and fixtures are available in or near the core for irradiations. When the reactor core is placed next to the D_2O tank and graphite reflector assembly near the beam port locations, thermal neutron beams become available. In steady state operation at 1 MW, the thermal neutron flux is 1×10^{13} cm^{-2}·s^{-1} at the edge of the core and 3×10^{13} cm^{-2}·s^{-1} at the central thimble. The peak flux during a maximum pulse is about 6×10^{16} cm^{-2}·s^{-1} with a pulse half width of ~10 ms.

II-2.1. Inherent design issues with PSBR

The PSBR first went critical in 1955 and is the longest continuously operating university research reactor in the United States. The initial reactor design utilized plate-type Materials Test Reactor (MTR) fuel elements with a 61-cm active fuel length and up to 93% enrichment. Seven beam ports were built into the facility design for analysing the nuclear properties of materials, determining reactor dynamics, and examining the effects of radiation on materials. After ten years of service, the reactor core design was changed to a TRIGA Mark III. The design conversion to a TRIGA core produced three major advantages for the reactor: (1) the reactor power was increased from 200 kW to 1 MW; (2) the reactor was moved to the low-enriched uranium safeguards category, since 20% enriched fuel elements are used in the TRIGA core and (3) pulsing capability was added to the core due to the inherent prompt negative feedback characteristics of the TRIGA fuel elements, which are a matrix of uranium and $ZrH_{1.6}$ moderators. Unfortunately, the design conversion also resulted in a partial loss of experimental capability for the facility, such that six of the seven beam ports are limited in neutron beam utilization. This is mainly due to the physical differences between MTR and TRIGA fuel element designs. Since the active length of a TRIGA fuel element (38.1 cm) is considerably smaller than the active length of an MTR fuel element (~61 cm), six beam ports, which were aligned with the MTR fuel, are now directed 12.7 or 27.9 cm below the core centre. In this existing beam port configuration, only beam port (BP 4) is located at the core centre. In addition, five of the seven existing beam ports could not be properly aligned to the core–moderator assembly after the design change. A schematic drawing of the existing reactor core, D_2O tank, graphite and seven beam ports extended toward the reactor core are given in Figure II-3. Therefore, the PSBR is not capable of simultaneously utilizing all the available beam ports with the current configuration of the beam ports and the core–moderator assembly.

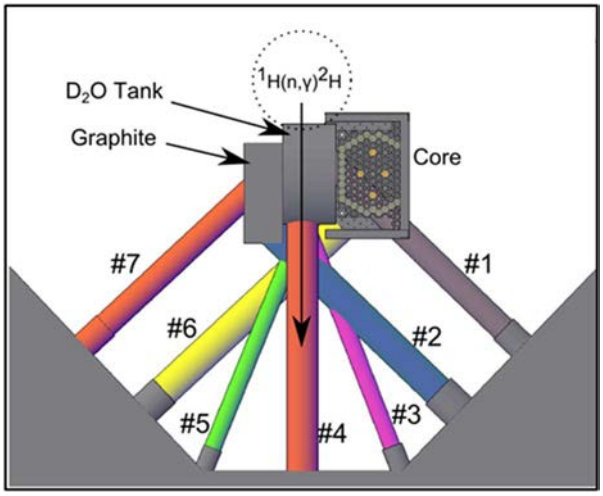

FIG. II-3. AutoCAD drawing of the existing PSBR core–moderator assembly layout with extended views of existing beam ports (top view) (courtesy of K. Ünlü, PSBR).

II-2.2. New core–moderator assembly design at PSBR

A significant redesign of the core–moderator assembly and beam port was complete to make full use of the PSBR's capabilities and to establish state-of-the-art neutron beam facilities. A new PSBR core–moderator assembly design and five new beam ports were completed. This design eliminates all the limitations of the existing design by increasing the number of simultaneously utilized beam ports from two to five and by mitigating the amount of prompt gamma-rays in the beam port facilities. The major constraints of the PSBR are mainly geometric factors such as available infrastructure in the beam hall, the tower design, geometrical

arrangement of the beam ports and the core and moderator designs. Furthermore, the thermohydraulic safety of the core was taken into account in the design process. The optimal design parameters and the neutronic performance of the new design were calculated [II-11–II-16].

The existing core–moderator assembly design is the main cause of the geometric mismatch of the beam port configuration. The key parameter in the design process is the calculation of the optimal size and shape of the moderator tank. A crescent-shaped moderator tank was chosen since it allows for the simultaneous utilization of five new beam ports. After the selection of the moderator tank shape, the second design step was the proper coupling of the moderator tank with the reactor core in order to eliminate the prompt-gamma contamination problem by minimizing pool water at the interface of the core–moderator assembly. This was achieved by keeping the faces of the top and bottom grid plates and the crescent-shaped moderator tank as close as possible (0.62 cm between the core and the moderator tank). The final step in the design process was how to support a new core design with a new reactor tower. The existing reactor core is supported by a tower through the bottom grid plate. The top grid plate is connected to the bottom grid plate. In the new design, the top and bottom grid plates are equal in size and smaller than the existing grid plates. As a result, the tower design was changed by installing four new support bars and two supports plates on top of the core. Figure II-4 shows the core–moderator assembly and tower design for the PSBR. Figures II-5 and II-6 show the D_2O moderator tank and reactor tower as delivered for installation.

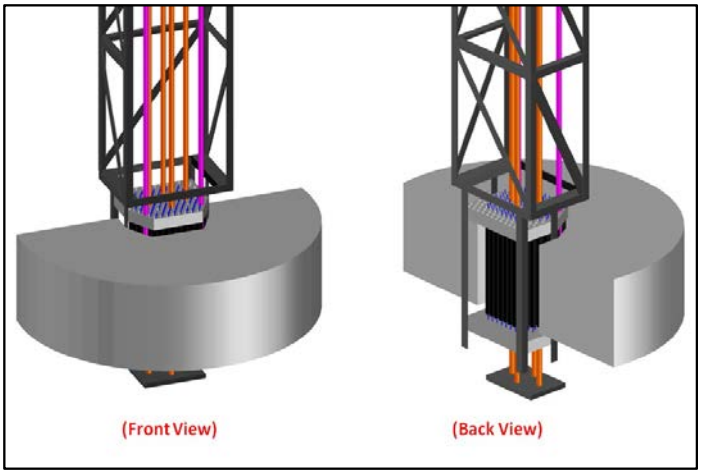

FIG. II-4. AutoCAD drawing of the new core–moderator assembly and tower design (courtesy of K. Ünlü, PSBR).

FIG. II-5. The D_2O moderator tank as delivered for installation (courtesy of K. Ünlü, PSBR).

FIG. II-6. Reactor tower with upper and lower grid plates as delivered for installation (courtesy of K. Ünlü, PSBR).

II-3.1. New beam port design at PSBR

The neutronic performance of the new beam ports is not only affected by the core–moderator assembly design but also the beam divergence, collimator system, filter material and other geometric factors like physical dimensions. In the optimization study, the neutronic design of the new reactor was explored with five beam port models without considering these factors. However, the final design features of each neutron beam port were based on the experimental facility to be used. Five neutron beam ports were designed for the new reactor. A cold neutron beam port which utilizes cold neutrons from three super-mirror neutron guide is considered. Therefore, there will be seven neutron beams available in the new facility. The design features of the new beam ports with the new core–moderator assembly are shown in Figure II-7. Three neutron guide tubes will be available to utilize the cold neutrons in the cold neutron beam facilities. Figures II-8 and II-9 show the installation of the new D_2O tank and beam ports.

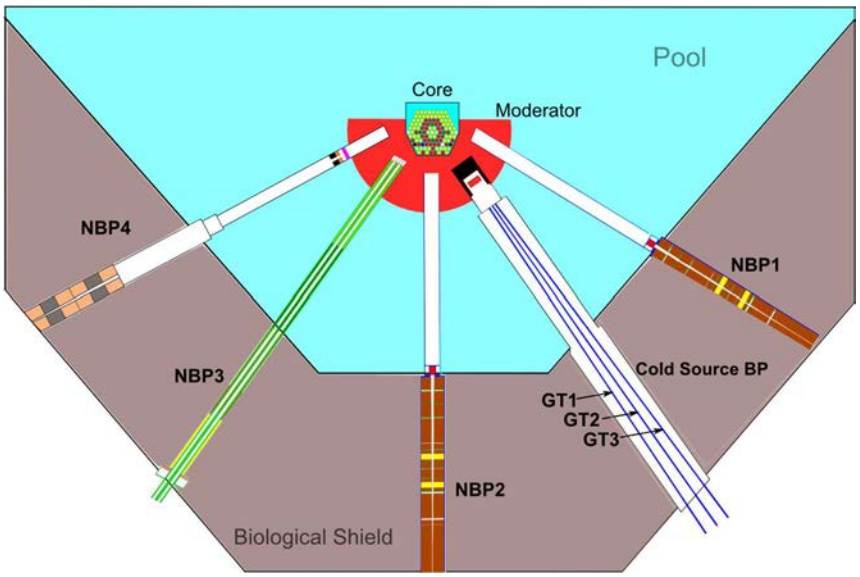

FIG. II-7. A schematic layout of the final design with four thermal neutron beam ports and one cold neutron beam port with three neutron guides (courtesy of K. Ünlü, PSBR).

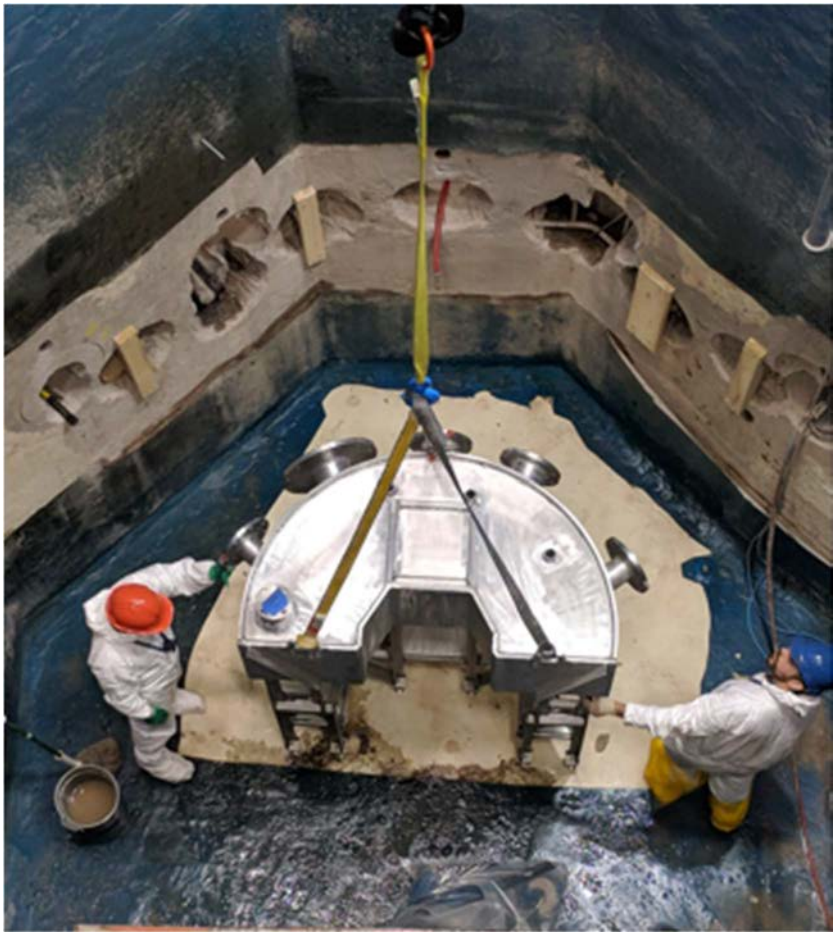

FIG. II-8. D_2O tank installation after taking out old beam ports and before installation of new beam ports (courtesy of K. Ünlü, PSBR).

FIG. II-9. Prof. Ünlü inspecting the new D_2O tank and new beam ports before filling the reactor pool and placing the reactor core for proceeding regular operation (courtesy of K. Ünlü, PSBR).

II-3.2. Penn State Breazeale reactor cold neutron source

A drawing of the PSBR-CNS is shown in Figure II-10. The PSBR-CNS is located inside a piercing beam port in the D_2O tank. The front end of the beam port is 15 cm away from the face of the reactor core. There will be a lead shield in front of the beam port that the mesitylene moderator is located. The beam port is heat shielded and evacuated. A 10 cm diameter, 2.5 cm

thick mesitylene moderator chamber is cooled by a circulating line of liquid-He from a cryorefrigerator located outside of the biological shield. The designs of both the Cornell and Texas Cold Neutron Source were initially considered. A thermodynamic analysis of a two phase-closed thermosyphon with vapour reservoir for cooling the moderator of the cold neutron source was carried out to investigate the operational characteristics and performance limit [II-17]. For this analysis, experimental results of a previous cooling system installed at University of Texas – Austin was considered. The data showed a limitation of the cooling capacity (only up to 4 W), due to lack of liquid (dryout) in the evaporator section of the thermosyphon. An analytic model was developed based on basic thermodynamic analysis that determines the dryout point for such a two-phase closed thermosyphon with reservoir (TPCTR). The model prediction of the dryout point for the TCNS cooling system was within 5% of the experimental data. Using this model, various parametric analyses were performed to investigate the effects of initial pressure, reservoir temperature, volume ratio (ratio of the volume of reservoir to that of thermosyphon) and working fluids. The results show that the dryout temperature varies the most when the volume ratio varies. In general, increase in volume ratio will increase the dryout temperature and hence the operational temperatures range of the TPCTR cooling system. Increase in initial pressure increases the dryout temperature under any volume ratio conditions. Decrease in reservoir temperature will increase the dryout temperature for lower volume ratio TPCTR systems. However, the effect of reservoir temperature decreases at higher volume ratios. From the parametric study of the fluids considered in this study it is concluded that usage of a two-phase closed thermosyphon will be sufficient for the PSBR-CNS. However, a circulating line of liquid-He from a Cryomech cryorefrigerator design will absorb much more heat load and will be a more effective cooling system. Therefore, a Cryomech cryorefrigerator with circulating liquid-He line was chosen for the PSBR-CNS cooling system. Figure II-11 shows some of the details of the PSBR-CNS mesitylene moderator chamber.

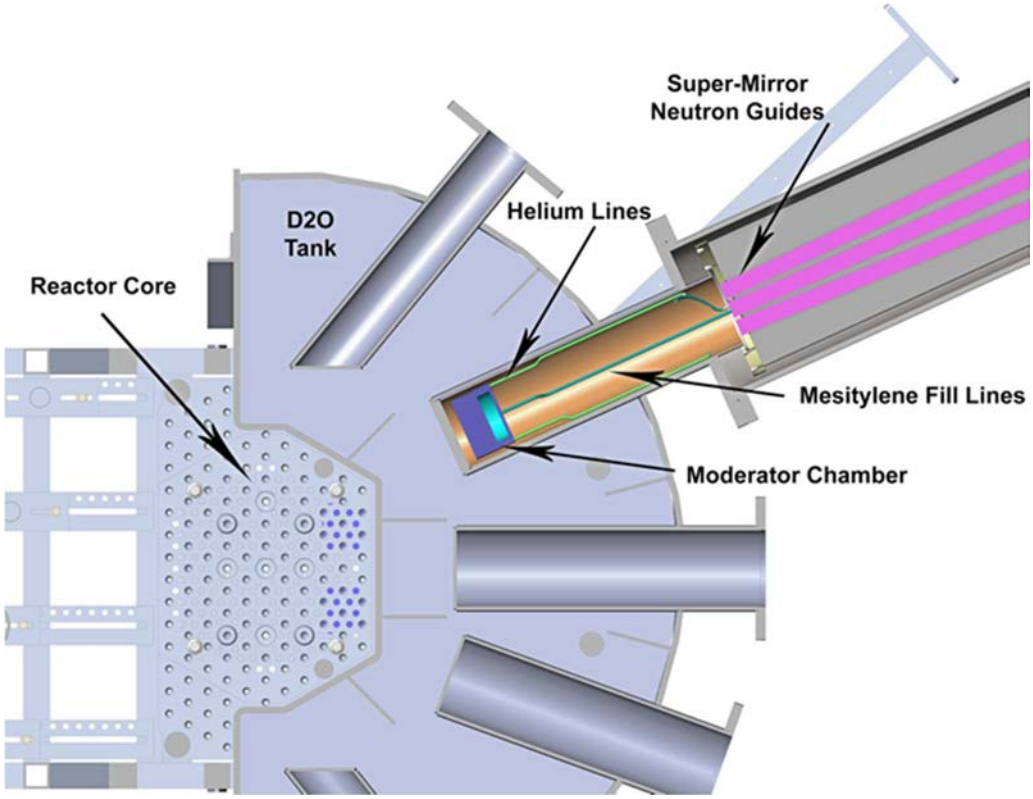

FIG. II-10. Drawings of the PSBR-CNS showing the front sections of the beam port embedded into the D_2O tank (courtesy of K. Ünlü, PSBR).

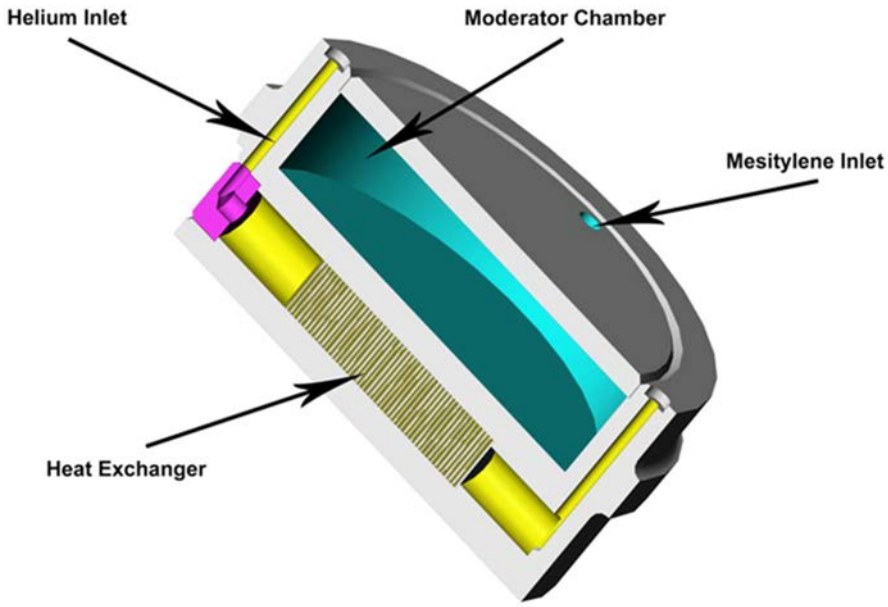

FIG. II-11. Detail drawing of the PSBR-CNS mesitylene moderator chamber (courtesy of K. Ünlü, PSBR).

II-3. SUMMARY AND CONCLUSIONS

Five new neutron beam ports were designed and installed at the PSBR facility. This new arrangement required cutting and removing a section of the existing biological shield and placing five new beam ports with various diameters depending on the intended neutron beam technique to be applied (Figs II-8 and 11-9). A mesitylene-based cold neutron source and three neutron guides will be installed in one of the beam ports. Four new experimental techniques (triple-axis spectrometer, conventional and time-of-fight neutron depth profiling, neutron powder diffraction or small angle neutron scattering, and prompt gamma activation analysis) will be added to the existing neutron imaging and neutron transmission facilities. The geometrical configurations along with the filter and collimator system designs of each neutron beam port were selected based on the requirements of the experimental facilities. An MCNP5 simulation results predicted that the thermal neutron flux would be increased by a factor of between 1.23 and 2.68 in the new beam ports compared to the existing design. In addition, the total gamma dose will be decreased by a factor of 100 in the new PSBR facilities.

The areas envisioned for the RSEC's new neutron beam port/beam laboratory are mostly for cutting-edge nuclear and materials science research. Some examples include: a neutron depth profiling facility for depth vs. concentration measurements, impurity determination of ^{3}He and ^{10}B in semiconductors, metals, and alloys; a mesitylene-based cold neutron source and cold neutron prompt gamma activation analysis for neutron focusing research, materials characterization, and determination of impurities in historically or technologically important materials; a neutron powder diffractometer or small angle neutron scattering for structural determination of materials; and a triple axis diffractometer to train students on neutron diffraction and perform preliminary structural determinations of materials. The majority of funds to develop and implement these techniques are already available at the RSEC. Most of the required equipment (e.g., neutron imaging systems, neutron activation analysis systems, neutron depth profiling chamber and the related data acquisition and processing equipment, and the prompt gamma activation analysis system) has already been purchased, and some of these techniques are already available at the RSEC with limited capacity. With the new and expanded

laboratory, the techniques and associated research projects will be improved, and new research projects will be available for the development of cold neutron beam and neutron guides.

The new and expanded laboratory will add new beam ports that are geometrically aligned with the core–moderator assembly for optimum neutron output at experimental positions. With state-of-the-art neutron beam facilities, coupled with the existing PSBR and RSEC capabilities will offer unparalleled research opportunities for Penn State faculty and graduate students in many disciplines and will provide an excellent testbed for development of instruments and experiments for researchers at Penn State, as well as other regional and national university researchers, industry, and national laboratories.

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Annex III.

COLD MODERATORS AT ISIS TARGET STATION 1

This article gives an overview of the development of the cold moderators at the ISIS Facility's Target Station 1 [III-1].

III-1. ISIS SPALLATION NEUTRON SOURCE: CONCEPT, DESIGN, HISTORY

At the end of 1970s and beginning of 1980s, most of the accelerators for nuclear physics were retiring, so spallation neutron sources were built as satellite or refurbished facilities in their places. That was the case for ISIS facility in the United Kingdom as well. The proton synchrotron for ISIS spallation neutron source was built in the hall originally constructed in the 1950s for the 7 GeV proton synchrotron, NIMROD. NIMROD closed down in 1978. The building housing of the target station existed (it was a part of NIMROD facility) with all its services. Foundations had to be constructed for the target station including extending the existing services, such as water and electricity, from the main services tunnels into the building. Most (about 90%) of the steel for the bulk shield was available at no cost from the old accelerator. This was machined on site to suit the target station. About 80% of the concrete which was used to construct the walls of the ISIS 'services area' was also available at no cost from the old accelerator. In those days, incoming proton energies at around 1 GeV were considered to be optimal for the neutron production for spallation reactions with heavy targets (U, W, Pb, etc.). In the case of the ISIS facility, the proton synchrotron (a 26 m mean radius, beam energy of 800 MeV with a cycling rate of 50 Hz) was originally designed to drive a depleted uranium target.

TABLE III-1. COST OF THE CONSTRUCTION OF THE ISIS SPALLATION NEUTRON SOURCE

Target station items	Cost £k	Totals
Target Assembly		
Primary target	114	
Moderator/reflector assembly	50	
Target services	250	
Moderator/reflector services	537	
Monitoring and controls	279	1280
Shield Assembly		
Bulk shielding	449	
Special shielding components	538	
Beam ports	956	1943
Remote Handling		
Remote handling cell	624	624
Spares	132	132
Grand Total		3979

Note: Originally, this was called the Spallation Neutron Source, but with the advent of the second target station it is now known as ISIS Target Station 1. These are the capital or investment costs including all the contracts placed for equipment, contract design services and installation contracts. Total laboratory labour used was 185 staff-years. (All prices at 1984 values.)

The most important milestones during the early days of the ISIS spallation neutron source are listed in Table III-2. Table III-3 shows the original specification of the cold moderators.

TABLE III-2. THE ISIS SPALLATION NEUTRON SOURCE MILESTONES (EARLY YEARS)

Date	Event
December 1976	Spallation Neutron Source proposal
June 1977	Project approved
November 1979	Construction of target station started
September 1980	Construction started in synchrotron room
November 1980	First magnets installed in synchrotron
January 1983	70 MeV beam achieved in injector
December 1983	Synchrotron ring complete
January 1984	Beam injected into synchrotron
April 1984	First acceleration of beam in synchrotron
September 1984	Beam extracted from synchrotron
December 1984	Beam on target - first neutrons
June 1985	Scheduled running starts
October 1985	Inauguration of ISIS
March 1987	Beam energy increased to 750 MeV
August 1988	100 μA proton beam current achieved

The main purpose behind the ISIS spallation neutron source's target, reflector and moderators (TRaM) design was the production of a wide variety of beams with appropriate spectral and resolution characteristics matched to the envisaged instrument suite. This has been achieved using four moderators in wing geometry: two ambient water moderators above and two cold moderators below the spallation target (see Figure III-1). The arrows labelled N and S refer to particular beam lines in the north and south of the experimental hall and are further described in Table III-3.

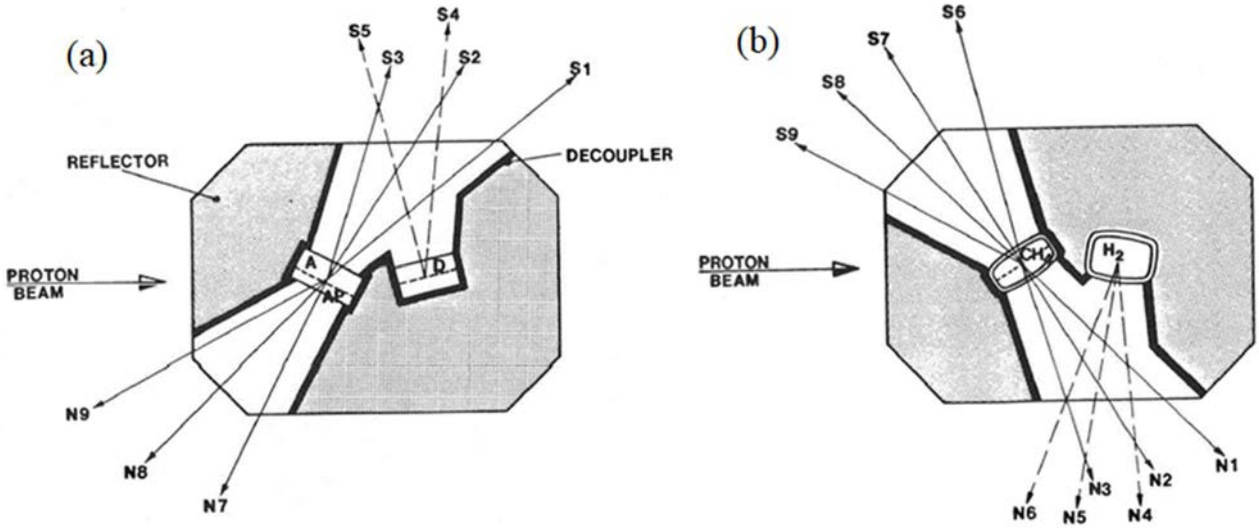

FIG. III-1. Initial idea for ISIS TS-1 TRaM design. Sections through the (a) upper layer of ambient water moderators, where the upstream moderator (A) is asymmetrically poisoned and the downstream moderator (D, also known as 'Merlin', is symmetrically poisoned) and (b) lower layer of cold moderators. Gadolinium poison layers are shown as dashed lines inside the moderator vessels. The arrows labelled N and S refer to particular beam lines in the north and south of the experimental hall. This figure by the authors of Ref. [III-2] is licensed under CC BY-4.0.

The target and moderators were surrounded with a reflector made of water-cooled Be rods. In its initial configuration (Figure III-2), SNS has seven beams viewing the high intensity, high resolution liquid methane moderator optimized for pulse structure, three beams of long wavelength neutron from liquid hydrogen moderator optimized for intensity and the remaining five beams viewing the ambient water moderators.

TABLE III-3. ORIGINAL SPECIFICATIONS OF THE COLD MODERATORS ON TARGET STATION 1

	CH_4 moderator	H_2 moderator
Moderating material	Liquid methane (4 atm)	Liquid hydrogen (p-H_2; 15 atm)
Operating temperature (K)	95	25
Position	Bottom front	Bottom rear
Height (cm)	11.5	12
Width (cm)	12	11
Thickness (cm)	4.5	8
Poison	0.05 mm thick Gd	N/A
Poison depth (cm)	2.25	N/A
Decoupler	B	N/A
Void liner	B	B/Cd
Beam Lines (angle to moderator normal)	N1(14), N2(1), N3(12), S6(13), S7(0), S8(14), S9(27)	N4(13), N5(0), N6(13)

The instruments shown in Figure III-2 can be referenced back to the moderator views of each beamline shown in Figure III-1.

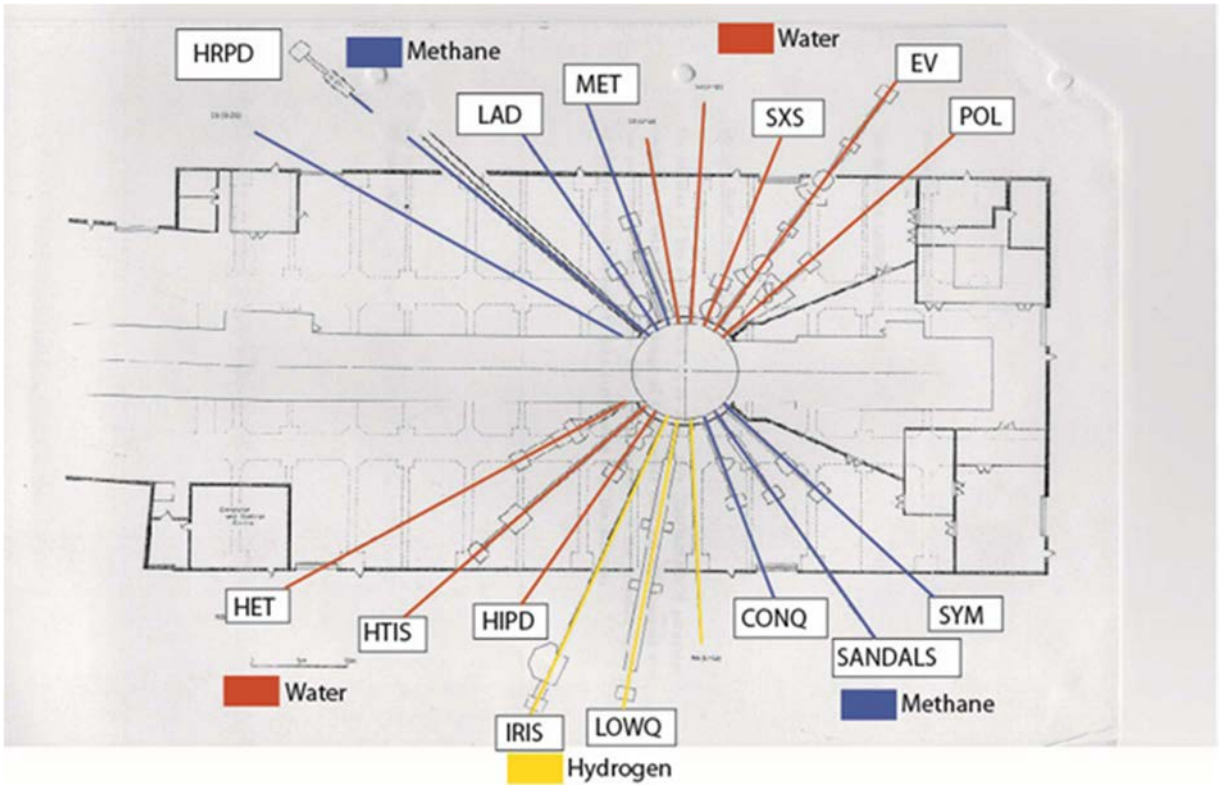

FIG. III-2. The original planned configuration of SNS (ISIS TS-1) instruments placed at the end of the beam lines in the experimental hall. This figure by the authors of Ref. [III-2] is licensed under CC BY-4.0.

The time structure of the pulse of neutrons (see Figure III-3) was of prime importance. The idea was to preserve the very sharp proton burst from the synchrotron (400 ns) by using relatively thin moderators, poisoned by Gd and decoupled from the reflector.

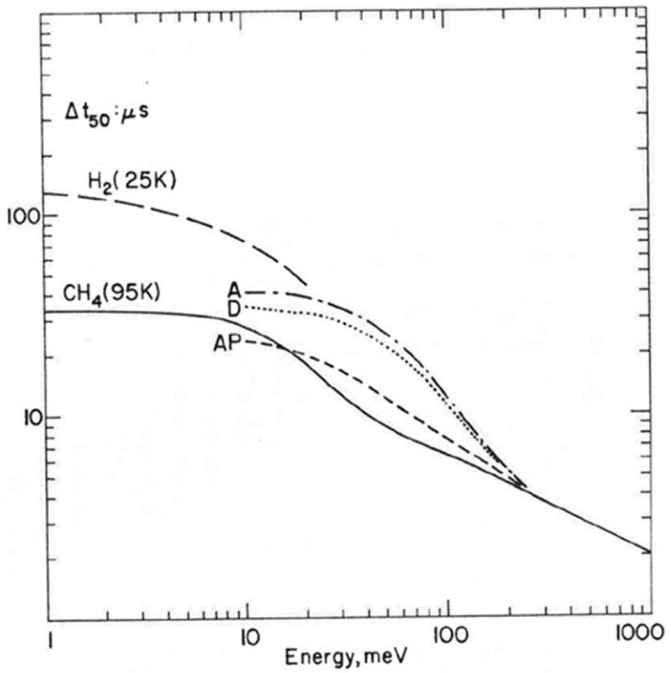

FIG. III-3. Predicted full width at half maximum (FWHM) of the six faces of the four TS-1 moderators as a function of energy. The faces are as labelled in Figure III-1, and the two CH_4 faces are symmetric. This figure by the authors of Ref. [III-2] is licensed under CC BY-4.0.

The intensity predictions shown in Figure III-4 were based on calculations with the Monte Carlo code TIMOC, experiments in the low current target station at Los Alamos, and experience at Argonne.

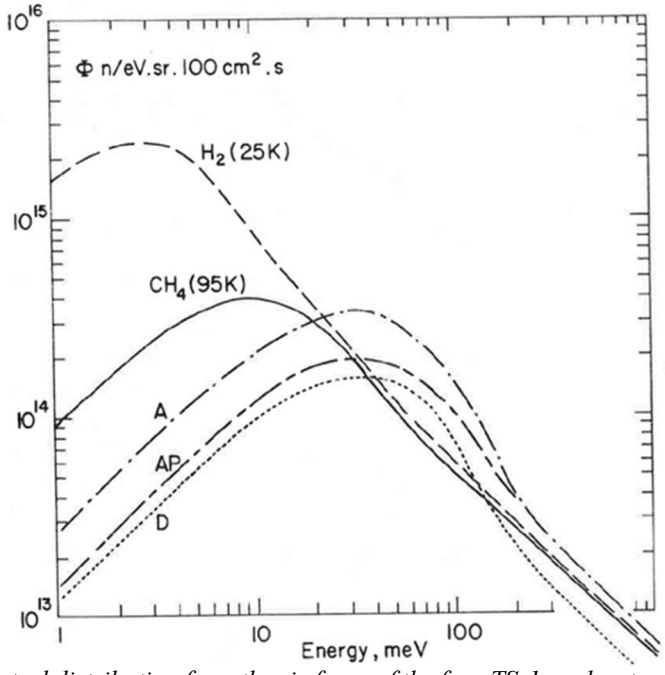

FIG. III-4. Predicted spectral distribution from the six faces of the four TS-1 moderators. The faces are as labelled in Figure III-1, and the two CH_4 faces are symmetric. This figure by the authors of Ref. [III-2] is licensed under CC BY-4.0.

First beam on at the ISIS facility occurred on 16 December 1984. As seen in Figure III-5, it took 7–8 years for ISIS to reach the level at which it has operated routinely. In the early days the ISIS synchrotron did not operate with its full complement of six (fundamental frequency)

RF cavities but with only four, and the output energy was limited to 550 MeV instead of the 800 MeV.

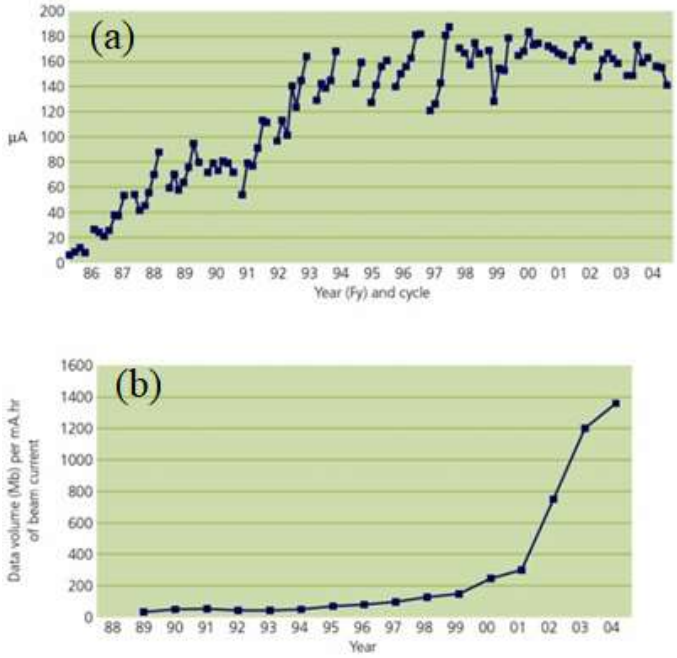

FIG. III-5. The plots show (a) the average beam current (in μA) per user cycle between 1985 and 2005, and (b) the amount of data taken per mA-hour of beam current in the same period. This figure by the authors of Ref. [III-3] is licensed under CC BY-4.0.

Since 1992, when ISIS output stabilised, output in terms of science (measured in terms of volume of data produced and published) has increased by a factor 20, due to enhancements made to the suite of neutron instruments (see Figure III-6).

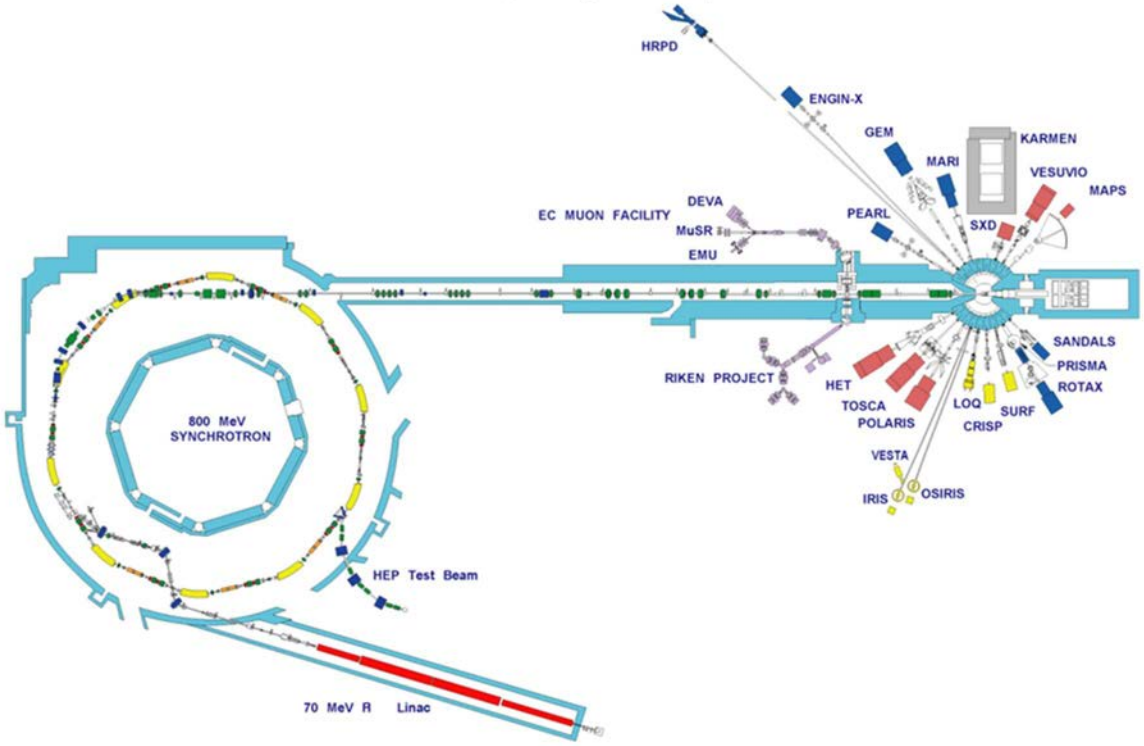

FIG. III-6. ISIS instruments in 1999. The colour coding (red, yellow, blue) of the instruments around the target station defines the moderator they view and matches that of the moderator types in the original planned configuration shown in Figure III-2 (courtesy of G. Škoro, ISIS Facility).

III-2. ISIS TARGET STATION 1: CURRENT STATUS

Cross sections of the baseline Target Station 1 (TS-1) TRaM assembly are shown in Figure III-7. The proton beam orientation is from left to right in this figure. The modern target consists of Ta-clad W rectangular plates inside a stainless steel pressure vessel. The reflector is made of water-cooled Be rods. The target and reflector coolant is a mixture of heavy water (82%) and light water (18%). As planned 35 years ago, there are four moderators in TS-1. Two decoupled, poisoned water moderators operating at room temperature are located above the target (see Figures III-1a and III-7c). The first, upstream water moderator ('A') has an asymmetrically positioned poison (Gd) layer. The downstream moderator ('D', also called 'Merlin') is centrally poisoned with a single Gd layer. The moderators are surrounded with 0.65 cm thick, boral layers (the neutron flightlines are lined with boral layers as well). Below the target there are the coupled liquid-hydrogen moderator and the poisoned, decoupled liquid-methane moderator (see Figures III-1b and III-7b). The hydrogen moderator operates at about 20 K with an estimated *p*-hydrogen fraction of 80%. The hydrogen moderator size is 12 cm (high) × 11 cm (wide) × 8 cm (thick). The liquid-methane moderator operates at 110 K and is centrally poisoned with a single, 50 μm thick, Gd layer. The liquid-methane moderator size is 11.5 cm (high) × 12 cm (wide) × 4.5 cm (thick). Their neutron flightlines are lined with 0.65 cm thick, boral layers. The same material is used as the methane moderator decoupler on the left, right and top (between target and moderator) sides of the moderator.

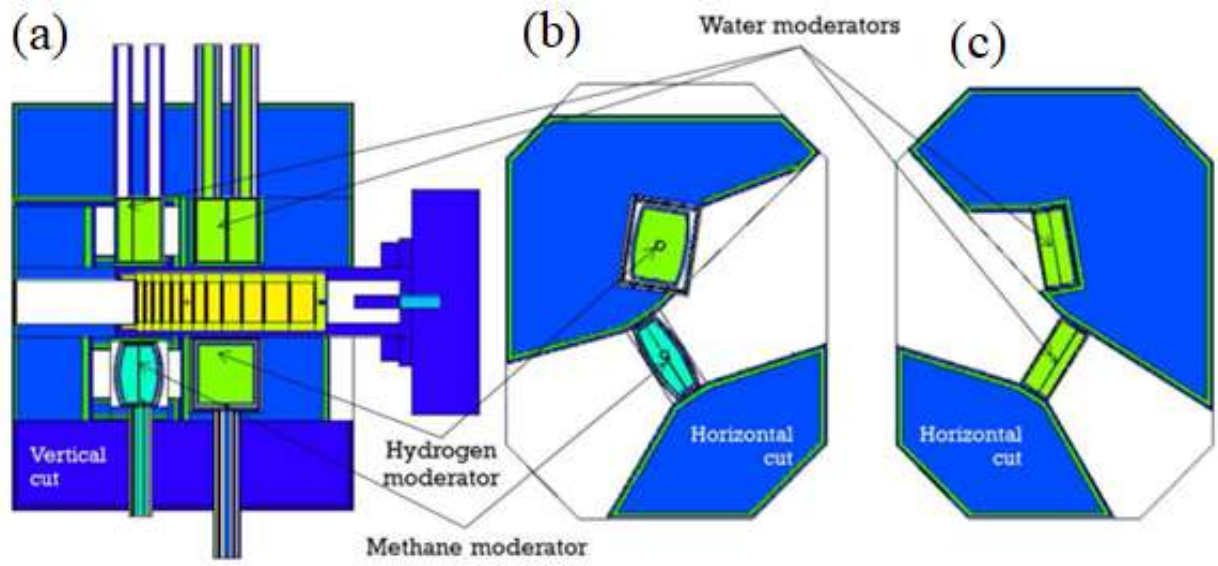

FIG. III-7. MCNPX model of the current ISIS Target Station 1 TRaM assembly. (a) vertical cut showing the upper ambient moderators and the lower cold moderators, (b) lower horizontal cross section showing the cold moderators, (c) upper horizontal cross section shown the ambient water moderators. Note that (b) and (c) are rotated 90° with respect to Figure III-1(b) and (a), respectively (reproduced from Ref. [III-4] with permission of Elsevier).

The calculated mean and peak brightness of the current TS-1 moderators for beam current of 160 μA are shown in Figures III-8 and III-9. The CEM03 physics model and ENDF/B-VII cross section library have been used in these calculations.

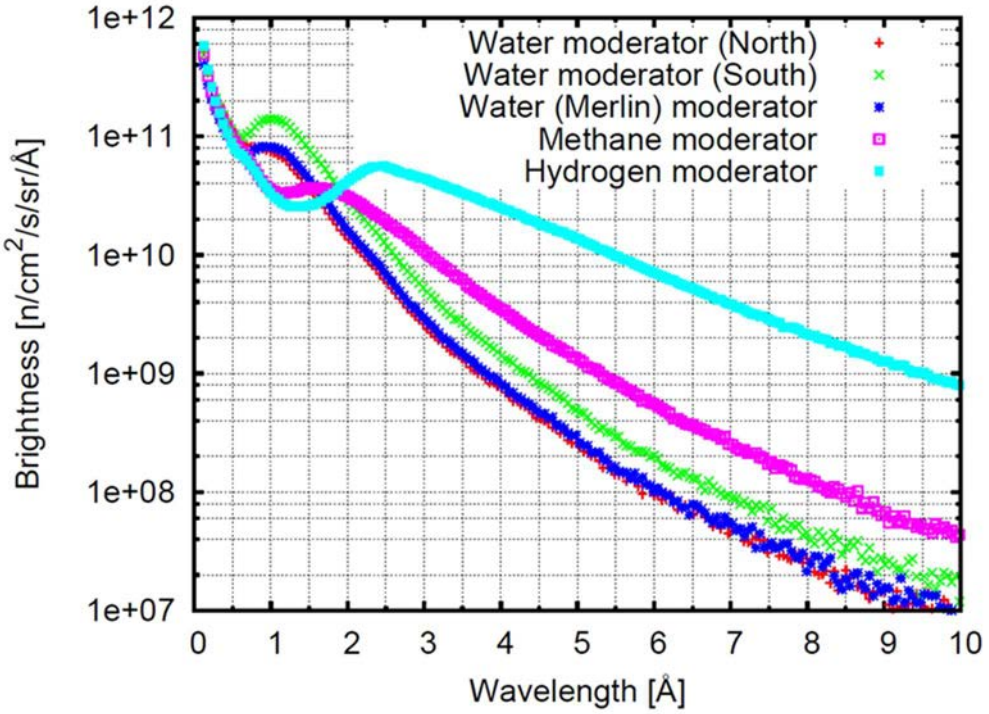

FIG. III-8. The calculated mean brightness of the current TS-1 moderators for beam current of 160 μA (reproduced from Ref. [III-4] with permission of Elsevier).

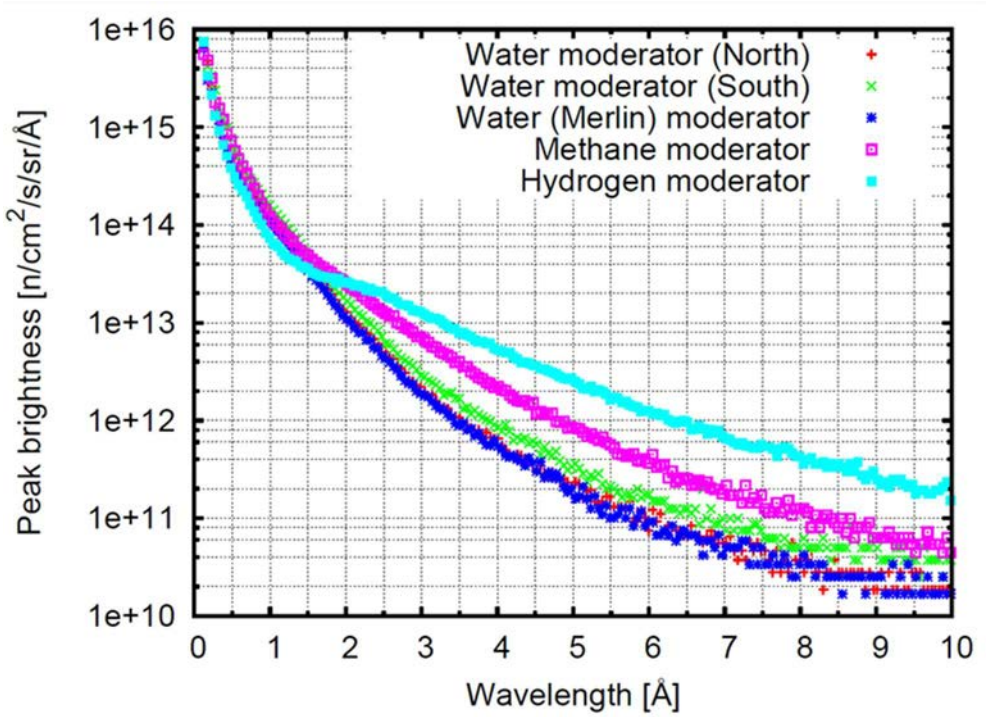

FIG. III-9. The calculated peak brightness of the current TS-1 moderators for beam current of 160 μA (reproduced from Ref. [III-4] with permission of Elsevier).

These four moderators serve 17 beamlines at ISIS TS-1 and provide neutrons for the experiments in the fields of spectroscopy (MAPS, MARI, MERLIN), molecular spectroscopy (IRIS, OSIRIS, TOSCA, VESUVIO), large scale structures (CRISP, SURF, LOQ), diffraction (HRPD, SXD, POLARIS, GEM, PEARL), disordered materials (SANDALS), etc. ISIS instruments as of 2018 (both from TS-1 and TS-2) are shown in Figure III-10 (cf. Figure III-6 for an earlier configuration).

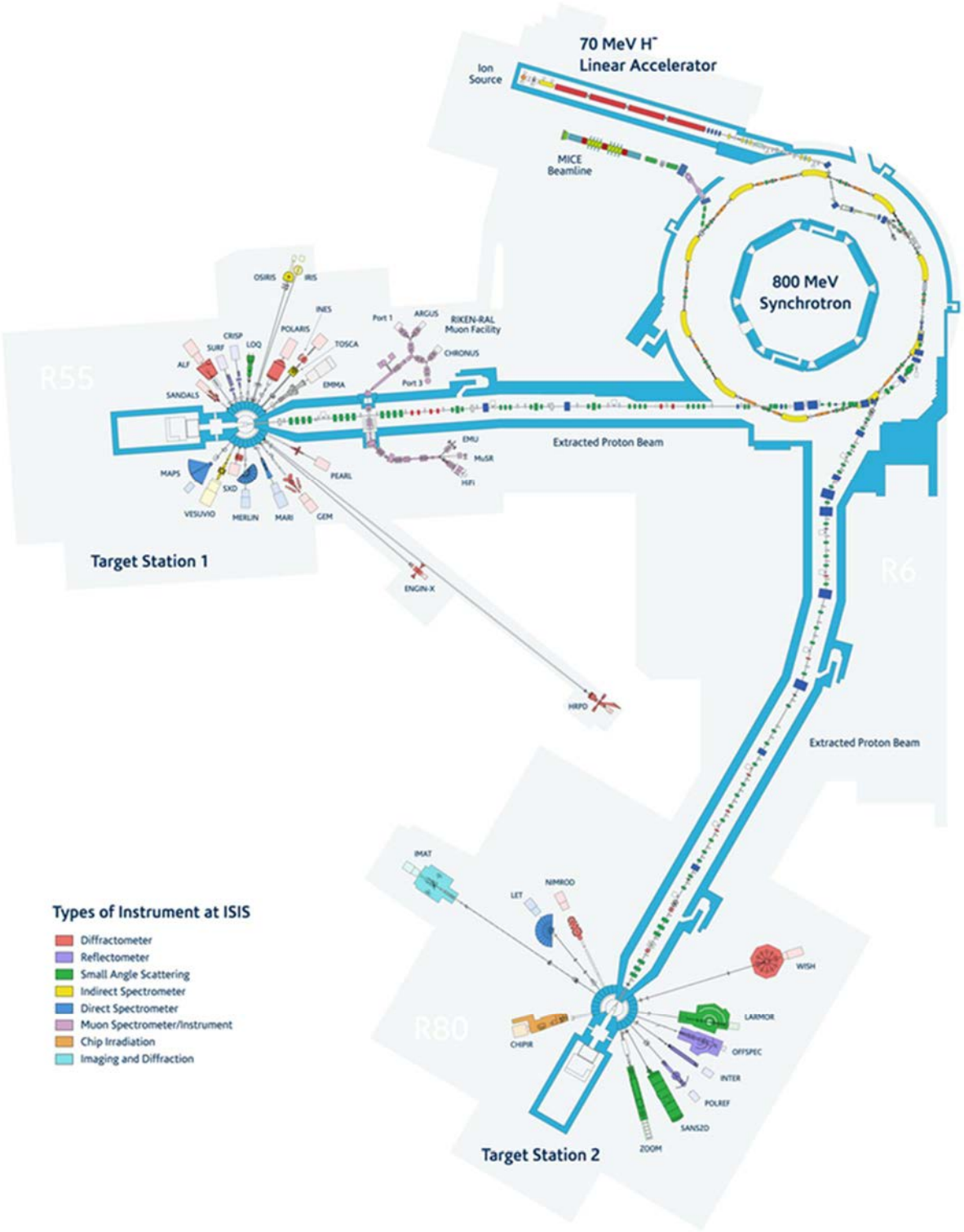

FIG. III-10. ISIS instruments in 2018 (courtesy of G. Škoro, ISIS Facility).

III-3. COLD MODERATORS ON TARGET STATION 1

III-3.1 Liquid hydrogen moderator

The hydrogen cryogenic system at ISIS TS-1 was designed and built in the 1980s. The vessel was machined from a solid block of N5 Mg-Al alloy. The shape of the liquid-hydrogen moderator is a compromise between a flat sided vessel favoured by neutronic considerations and a spherical pressure vessel (Figure III-11). Stressing was carried out using the NASTRAN finite element analysis software. This resulted in a wall thickness of 8 mm for a pressure differential of 15 bar.

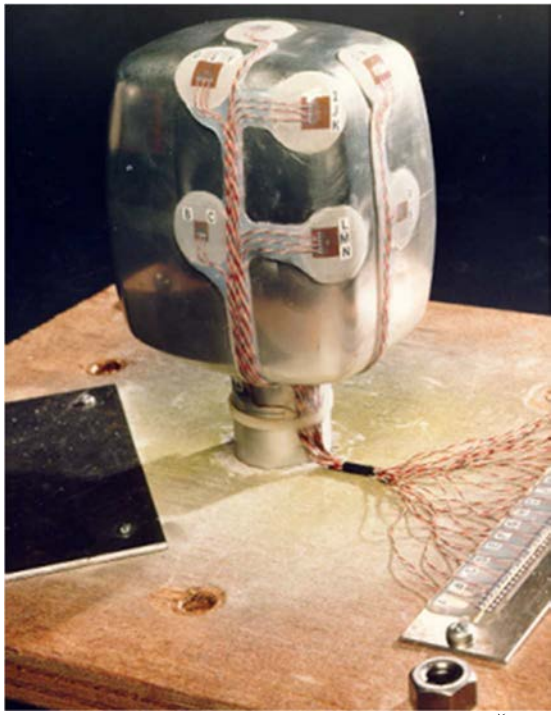

FIG. III-11. Hydrogen moderator can (courtesy of G. Škoro, ISIS Facility).

The alloy vessel was friction welded at its neck to austenitic stainless steel just below the beam line point. Likewise, the vacuum vessel was also friction welded at an adjacent point. The vacuum vessel, which was nominally shaped to match the main moderator vessel, was made from N8 Mg-Al alloy and is 3 mm thick. The minimum gap between the main vessel and the vacuum vessel is 3 mm and careful positioning and construction was necessary to avoid any chance of touching. The outermost tertiary vessel further encloses the vacuum vessel, as described earlier, creating a He blanket between the two. The assembly is designed to be replaced as a complete unit. In high radiation flux areas, frozen constituents of air can constitute a serious hazard on account of highly volatile ozone and nitrides of oxygen. A secondary containment was added to the He system to ensure a surface temperature always above the freezing point of such materials. The interface is charged with He gas. This containment extends over the moderator unit and over the entire length of the transfer lines to the hydrogen cold box.

Figure III-12 shows the circuit diagram of the system. The designed 15 bar at the highest pressure point of the circuit is about 2 bar above the critical pressure making the operational gas at 20 K supercritical. However, operating experience has showed that subcritical pressure boiling does not occur, and the system is run at about 10 bar, at which pressure the hydrogen is liquid.

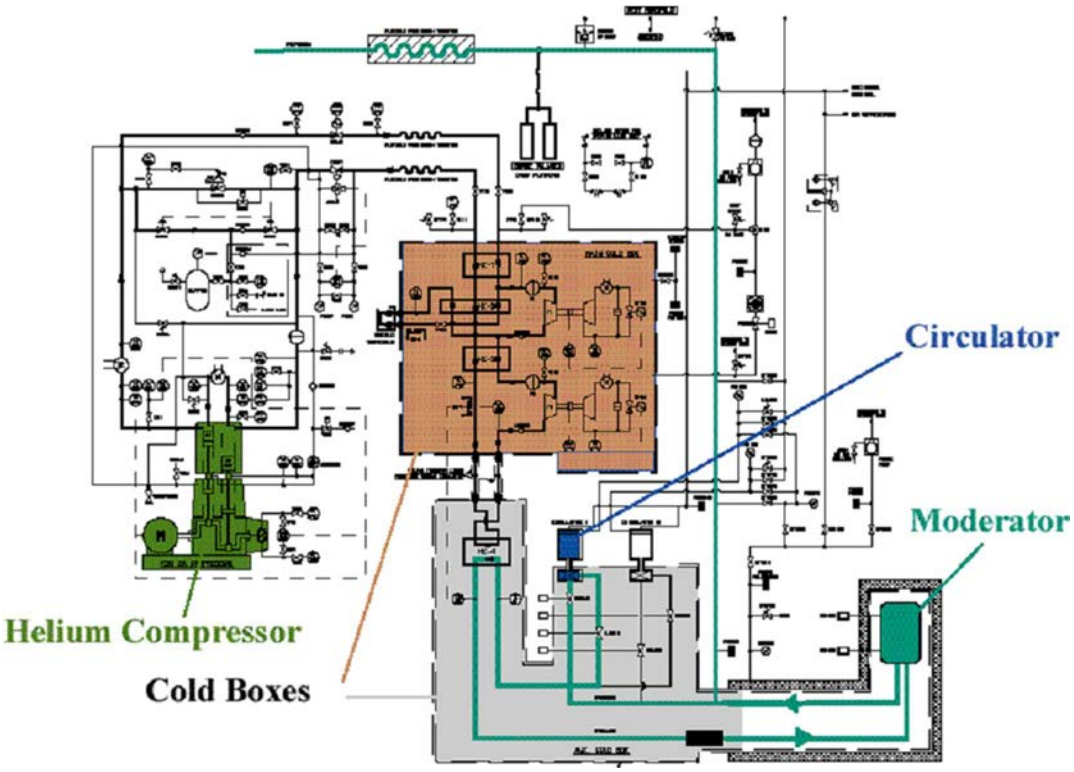

FIG. III-12. A schematic diagram of the principal components of the hydrogen moderator circuit (courtesy of G. Škoro, ISIS Facility).

The refrigeration is provided by a two-stage 'Brayton' cycle with a maximum pressure range of 16 to 2 bar abs across two turbines in series. Helium gas is compressed in a two stage Sulzer K90 oil free compressor housed in an enclosure within the ISIS experimental hall. After compression, the He is cooled in a water-cooled heat exchanger. It is then piped to the services area and passed over the drum feed to the main cold box which contains three heat exchangers and the two high speed turbines. The design gas flow is 35 g/s and the design output is 600 W at 20 K. Gas from the second turbine is passed through a transfer line to a second cold box which contains a fourth heat exchanger which interfaces the cold He with the hydrogen loop. The second cold box also houses the circulators and their isolation cryo-valves. The electrical heater which controls the main loop is in the main cold box on the return line from the second box. The hydrogen pressure is held between limits approximately 1/2 bar apart by a pressure control system which admits or vents gas accordingly. The hydrogen temperature is controlled indirectly by an electrical heater in the refrigeration loop which operates in conjunction with a temperature sensor in the hydrogen cold box. This sensor is sited in the moderator flow leg as close as possible to the transfer line connection.

III-3.2. Liquid methane moderator

Methane has significant neutronic advantages over water or liquid hydrogen. It has a high density of hydrogen and of low-energy vibrational modes, giving an efficient thermalisation. The Maxwellian region provides very good intensity at relatively long wavelength with narrower time pulses than would result from hydrogen. A liquid methane moderator has been in use on ISIS since the facility started. The moderator consists of an Al alloy can (volume of ~0.5 litres) with a Gd poison foil positioned centrally through the vessel shown in Figures III-13 and III-14. This gives pulse widths in the slowing down region of, typically, 35 μs.

FIG. III-13. Methane moderator 28 (22/12/2003). This figure by the authors of Ref. [III-5] is licensed under CC BY-4.0.

FIG. III-14. Methane moderator 28 (22/12/2003). This figure by the authors of Ref. [III-5] is licensed under CC BY-4.0.

The general design and materials used were similar to those of the hydrogen system. The same mode of assembly was adopted but, without the need for a tertiary containment, the overall construction was much simpler. A Gd layer required on the median line was assembled using an Al frame to retain the shape. This was slotted into the main feed tube and welded. The volume of the methane moderator was half that of the hydrogen moderator, but the rest of the circuit was almost the same since the transfer lines were standard and followed the same route. The maximum working pressure of the system of 4 bar resulted in a wall thickness of 3 mm which was the same as the thickness of the vacuum vessel. No superinsulation was used in either moderator, and the thermal losses were minimised by attention to detail of the internal mounting.

The designed flowrate of liquid methane is 97 g/s against a head loss of approximately 1.6 bar. The pressure at the delivery point of the circulator is normally 4 bar, so that the lowest pressure in the system at 2.4 bar represents a saturation temperature of approximately 123 K. Refrigeration is by a Philips PG1O2S Stirling cycle machine using He as a refrigerant. The unit is cooled by a chiller which provides water at a controlled 2–3 °C. The refrigerator produces 1000 W of cooling at l00 K and is run at maximum power at all times, temperature control being provided by an electrical heater.

Figure III-15 is a simplified flow diagram of the system in its normal operating mode. There are three independent pressure control systems: main loop, condenser, and dump tank. All three

systems share a common feed line and a common vent line connected to main distribution panels outside the area. Each system has inlet and exhaust valves operated by their individual pressure monitoring systems to maintain pressures within 1/2 bar. Platinum temperature sensors are sited in the transfer box which is between the refrigerator and the transfer line. Monitoring is made immediately before and after the transfer line, on each side of the refrigerator, and just before the condenser. The sensor used for overall temperature control is that in the flow leg just before the outlet to the transfer line.

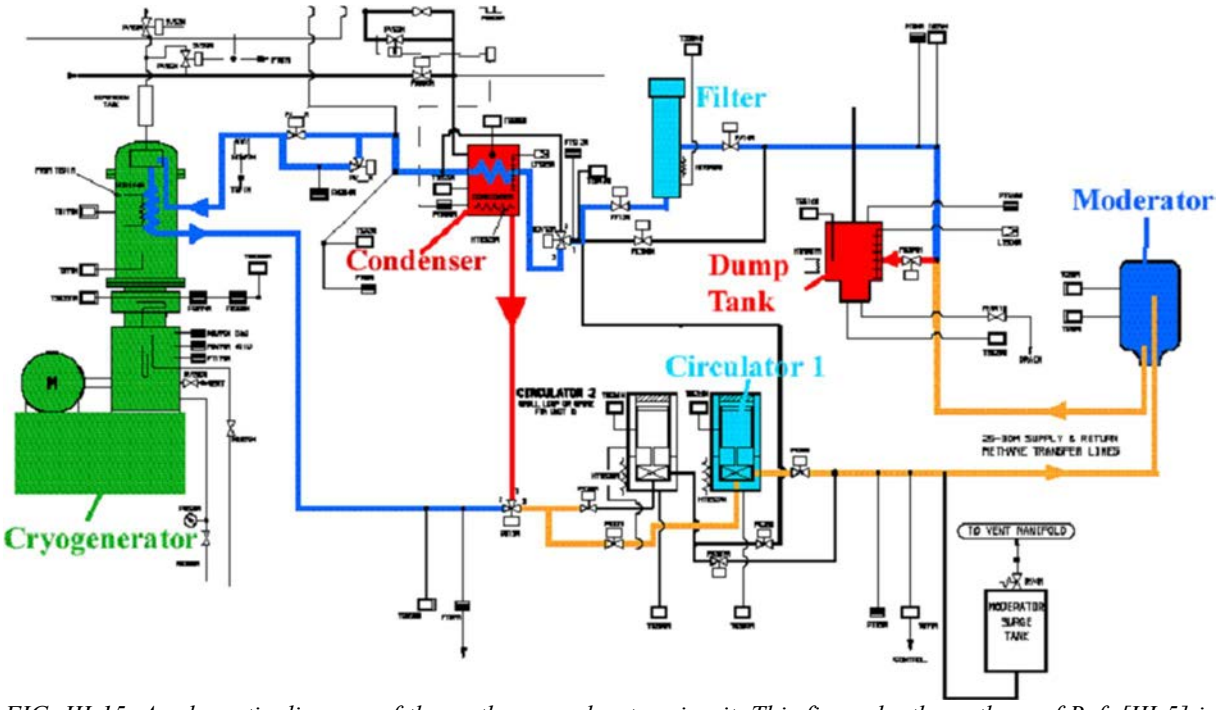

FIG. III-15. A schematic diagram of the methane moderator circuit. This figure by the authors of Ref. [III-5] is licensed under CC BY-4.0.

III-3.3. Cold moderator services

All service equipment for the TRaM assembly is built on rail-mounted platforms forming a train which is used to transfer the assembly between the operating position and the remote handling cell. All service pipes and cables to the movable train pass over one of two spring-loaded drums, which take up all available slack, or a rolling drag chain. Pipes carrying hydrogen or methane gas to the refrigeration equipment on the train are double walled for added safety with an inert gas supply to the annular space between them. Monitoring of the pressure in this annulus can provide a clear indication of gas leakage from the inner membrane. Temperature measurement on the hydrogen system is by Ge diodes, which are readily replaceable. The methane system uses Pt thermometers which can also be replaced without entering the vacuum chamber. Remote pressure monitoring of both the hydrogen and methane systems is by very reliable, radiation tolerant 'SHAEVITZ' strain gauge devices.

Figure III-16 shows a photograph of the partly dismantled TRaM assembly with both the hydrogen and methane moderators visible. In operation, moderators are subject to dose rates of about l000 Gy/h. This requires the systems to have no organic materials, so metal seals are required. Replacement of the moderators is performed using fully remote handling techniques in a purpose-built handling cell incorporated into the target station structure. The refrigeration equipment together with all cryogenic services and monitoring are situated within a shielded services area where operational dose rates are typical 1–2 Sv/h. In this area the decay of short

lived activity, mainly for the water cooling circuits for the TRaM, means that hands on servicing is possible after a decay period of about 1 hour.

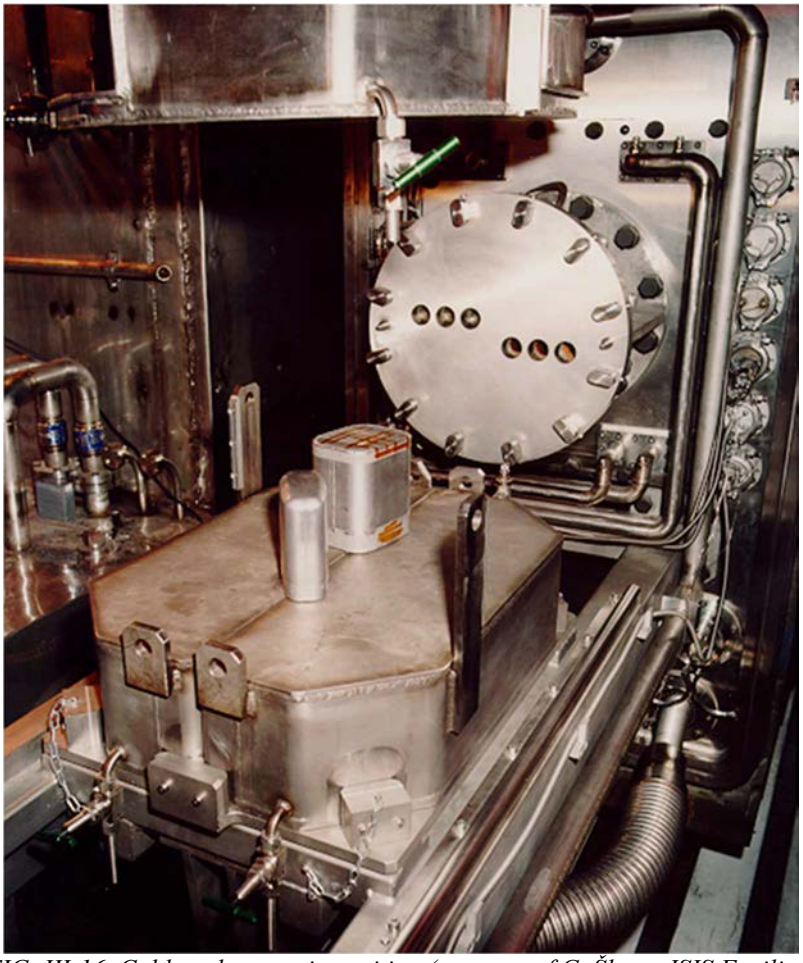

FIG. III-16. Cold moderators in position (courtesy of G. Škoro, ISIS Facility).

When warmed up, both of the systems vent into outside storage tanks rather than straight to atmosphere. This affords tighter control over the venting, and in the case of methane allows decay of the short half-life isotopes. However, direct atmospheric venting is still possible in an emergency. Venting of the storage vessels is carried out from the pressure control panels which routes the gas out through the dedicated high level vent.

III-4. OPERATIONAL EXPERIENCE AND CHALLENGES

Over the lifetime of a facility the relevant legal requirements may change as a response to specific incidents or maybe as a result of increased understanding of risks and industry best practice. In the case of ISIS moderators, several regulations and standards are relevant to moderator design, notably the pressure directive PD 5500[29] for the moderator cans and the explosive atmosphere/gases regulations (ATEX[30]/DSEAR[31]). The ATEX/DSEAR regulations in particular, have changed over the lifetime of ISIS leading to increased cost and complexity for future upgrades which adhere to stricter rules. PD 5500 was formally British Standard 5500, which early ISIS moderators were designed to comply with it. However, as it was not consistent

[29] British Standards Institution, Specification for unfired pressure vessels, PD 5500: https://www.bsigroup.com/en-GB/standards/pd-55002021/.
[30] Health and Safety Executive, ATEX and explosive atmospheres, https://www.hse.gov.uk/fireandexplosion/atex.htm.
[31] Health and Safety Executive, The Dangerous Substances and Explosive Atmospheres Regulations 2002, https://www.hse.gov.uk/fireandexplosion/dsear.htm.

with an EU pressure vessel standard, it was withdrawn, and its status changed from BS to published document (PD). However, ISIS moderators are still designed to comply with it.

Also, over the lifetime of ISIS, the regulatory approach to radiation protection (IRR, IRR99[32] and now IRR18[33]) and radioactive waste in the UK has changed. Disposal options that previously existed for moderators may no longer be viable, although others such as combustion may now be available due to new facilities being built. The radioactive waste disposal has to also be considered when selecting moderator materials as it is unlikely to be acceptable to choose a material for which a disposal option is not available. ISIS is relatively fortunate in that it is not considered a 'licensed nuclear site' under UK regulations which significantly increases its operational flexibility including for moderator changes.

III-4.1 Operational experience with liquid methane

While methane is an excellent moderator material, it suffers from radiation damage which leads to operational difficulties. Under ionizing radiation, methane polymerises resulting in the production of oils, waxes, and solids. Considerable quantities of hydrogen gas are also produced. From the outset of ISIS operations, there was, as expected, clear evidence of radiation damage to the methane. When components of the circuit such as filters and circulators were removed for servicing, a mixture of hydrocarbons was found. The viscosity of the mixture recovered from the circuit steadily increased with increasing irradiation. In the original design, the cryogenic system was emptied by removing the pressure and allowing the methane to boil off. It was recognised that this would result in non-volatile hydrocarbons remaining in the circuit. During the first three years of operation of ISIS this 'contamination' of the circuit was the only significant operational problem. This was the period during which the ISIS proton current was relatively low. As the integrated proton current was increased, the cryogenic system became less stable and periodic sharp pressure spikes occurred. These were believed to be the result of the sudden evapouration of a small volume of liquid methane in the circuit.

Generally speaking, it is not possible to predict the quantity of hydrocarbons in the form of oil, wax, and solid. A practical way to keep the system clean is to replace the liquid charge at operational temperature. The frequency at which the liquid is changed depends on the perceived rate of oil production. If any pockets of low flow exist, particularly in the moderator itself, impurities could progress through the early phases to solid material and form a platform on which a blockage could build up. The only way to address this is to streamline the flow pattern to design out low flow node points. So, a facility has been built into the system to enable fluid changes to be carried out every day. Surplus refrigerator capacity is used in a condenser to produce a fresh charge of liquid methane in a completely separate circuit. At the same time a dump vessel is precooled ready to receive the old, contaminated liquid. Remotely driven cryogenic diverter valves allow a small loop to be configured to keep the refrigerator in a standby state, and flow is then diverted from the condenser into the main loop displacing the old liquid into the dump tank. This operation takes around one minute, after which the original loop can be re-instated. The old liquid is then boiled away in a controlled manner. Heavy oils are washed out of the tank periodically with a suitable solvent. Data taking time is lost during the on-line liquid replacement.

[32] The Ionising Radiations Regulations 1999, https://www.legislation.gov.uk/uksi/1999/3232/contents/made.
[33] The Ionising Radiation (Basic Safety Standards) (Miscellaneous Provisions) Regulations 2018, https://www.legislation.gov.uk/uksi/2018/482/contents.

Formation of high mass hydrocarbons eventually leads to a blockage in the moderator. Figure III-17 shows the increase in pressure drop across one of the moderators as a function of operation time.

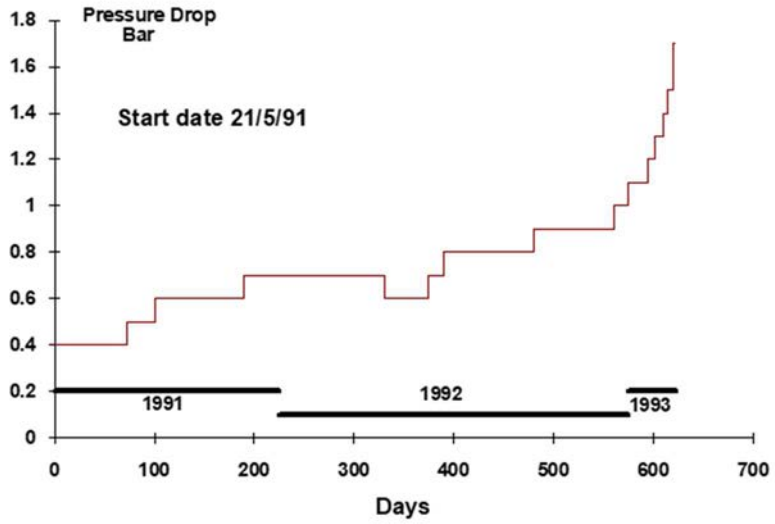

FIG. III-17. The increase in pressure drop across the methane moderator as a function of operation time. This figure by the authors of Ref. [III-6] is licensed under CC BY-4.0.

This moderator was dismantled in a hot cell and Figure III-18 shows the extensive solid deposits discovered on the interior of the moderator vessel.

FIG. III-18. The build-up of 'carbon-like' deposits. This figure by the authors of Ref. [III-6] is licensed under CC BY-4.0.

In addition, the neutron spectrum degrades significantly as the deposits build up (the illustration of such a behaviour is given in Figure III-19). To mitigate these effects the current practice is to replace the moderator after about 100 days in operation which gives an acceptably stable operation. This task takes four weeks.

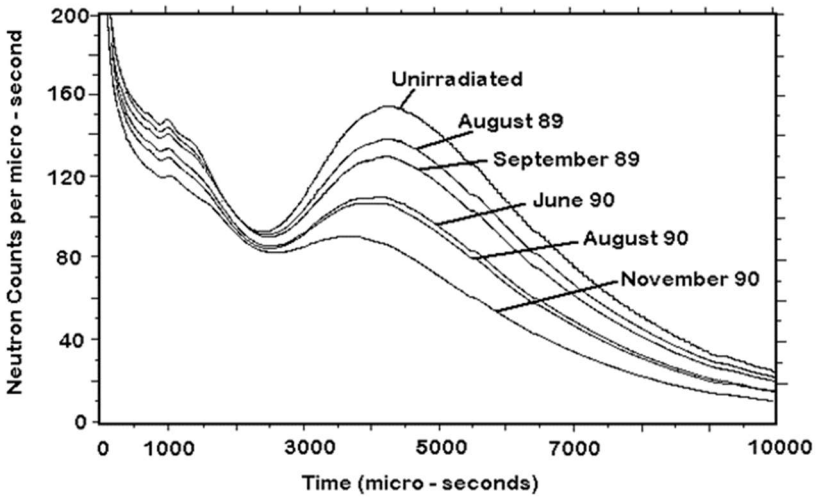

FIG. III-19. The effect of irradiation of the neutron spectrum. This figure by the authors of Ref. [III-6] is licensed under CC BY-4.0.

III-4.4.1. Liquid ethane experiments

Because the methane moderator lasts for only about 2.5 cycles before operation becomes difficult and running erratic, the idea to replace it with liquid ethane was explored in the late 1990s. At that time, there was some evidence that from a radiological damage point of view ethane, and maybe propane, would be better, but the neutron moderation properties were unknown. Liquid ethane was tested in the ISIS TS-1 methane moderator in 1998 and 1999. Ethane temperature was at ~110 K during tests in 1998 and at ~120 K during tests in 1999. Methane temperature was at 105–110 K in subsequent runs (both in 1998 and 1999).

The target/moderator group measured spectrum and line shapes to make comparisons with the methane moderator results. A significant gain of almost 40% has been observed in the neutron wavelength region around 1Å (see Figure III-20).

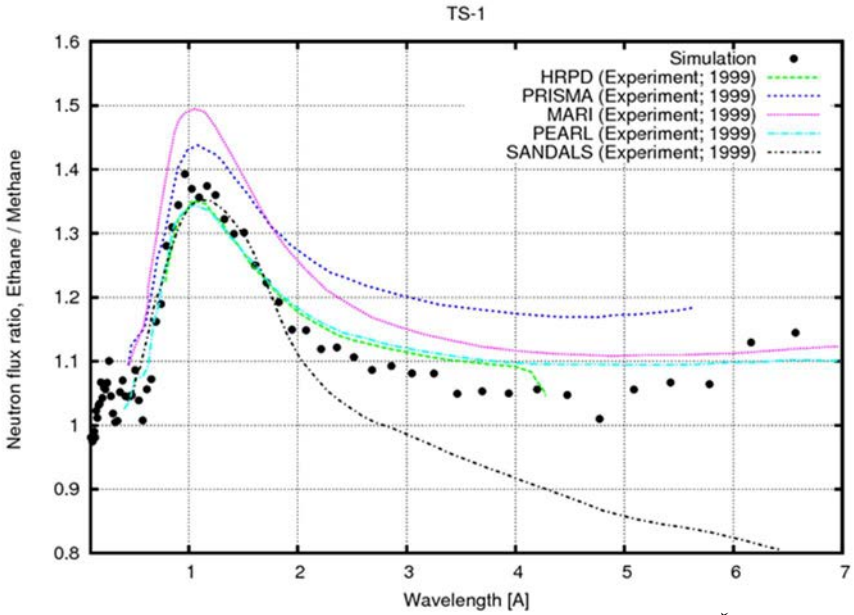

FIG. III-20. Ethane/methane comparison – intensity (courtesy of G. Škoro, ISIS Facility).

However, the measured pulse time profiles were broader by about 10–15% than for methane (see Figure III-21), so the idea of using liquid ethane was abandoned.

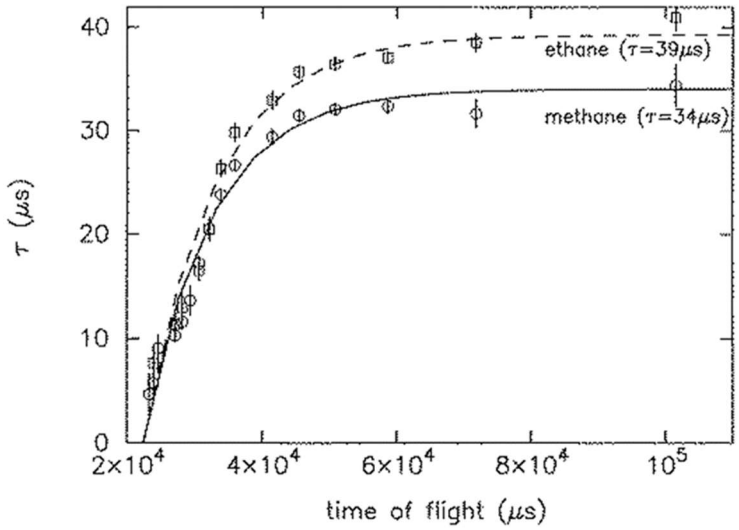

FIG. III-21. Comparison of the time profiles of neutron pulses from ethane and methane cold moderators at ISIS TS-1. This figure by the authors of Ref. [III-7] is licensed under CC BY-4.0.

III-4.2 Operational experience with hydrogen

There have been essentially no operational problems with the hydrogen system for many years. The moderator itself was planned to be a supercritical liquid hydrogen moderator with a Cd decoupler, but it never ran supercritical and the decoupler was removed in 2006. There are five instruments that view the hydrogen moderator: CRISP, IRIS, LOQ, OSIRIS, and SURF (Figure III-6). The hydrogen system is purged and filled with low pressure He after each user cycle, then purged and refilled with a new batch of normal hydrogen (75% *o*-H_2, 25% *p*-H_2) at the end of the shutdown. This generally happens about a week before the user run starts as the moderators need to be cold during 'beam physics' time. The original design of the hydrogen cryogenic system had a very small amount of ferric oxide (Fe_2O_3) catalyst (see Figure III-22) that was not of sufficient size to convert the volume of hydrogen in the system at any noticeable rate. There has also been no reactivation or increase in volume during the lifetime of the cryogenic cold box.

FIG. III-22. Ferric oxide catalyst mesh holder inspected in December 2015. This figure by the authors of Ref. [III-8] is licensed under CC BY-3.0.

The *o*-/*p*-hydrogen ratio effect in the TS-1 hydrogen moderator was practically unknown, but never a high priority to improve or to discover the nature of how it changed through time. Due to the ongoing ISIS TS-1 Project, the need for better understanding of the ratio of spin isomers in the liquid hydrogen moderator has become greater. A detailed study has been performed in an attempt to characterize the *o*-/*p*- hydrogen fraction using data from the LOQ incident beam monitor collected over the last 10 years (see Figure III-23).

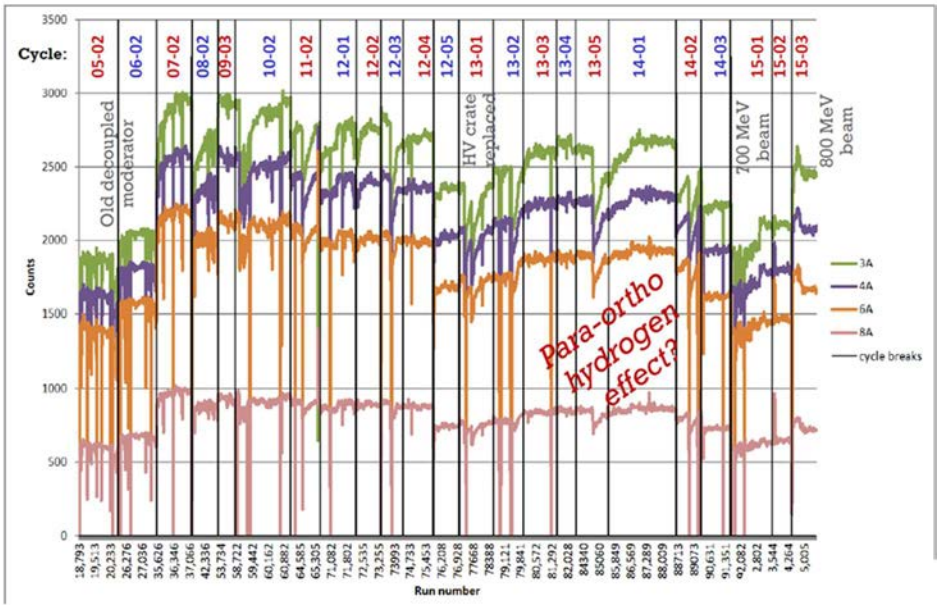

FIG. III-23. Wavelength dependent count-rate from the beam monitor of the LOQ instrument extracted from the 10 year record (courtesy of G. Škoro, ISIS Facility).

The idea was that the variations of count rates (and wavelength dependence of these variations) in a single cycle, if combined with Monte Carlo simulation results, could give an indication about the *o*-/*p*- conversion. The simulations were important for an interpretation because neutron intensity fluctuations as a function of wavelength depend strongly on the starting/final values of the *p*-hydrogen fraction (especially at long wavelengths). So, the cycles where variations were relatively large or where something happened (for example, the hydrogen system was purged and restarted during a cycle) were of special interest. The analysis of those special events and comparison with Monte Carlo simulations showed that the hydrogen behaviour is compatible with the so-called 'natural conversion scenario' and that the maximum value of the *p*-fraction during the last 10 years was around 80%.

This value agrees well with the value obtained from the direct measurement of neutron transmission through thin hydrogen samples (with different *p*-hydrogen fractions) using the VESUVIO instrument at ISIS [III-9–III-10]. This method includes measurements of thermal conductivity of the same hydrogen samples using a *p*-hydrogen gauge (and a *p*-hydrogen generating cell) originally built for use by the TOSCA instrument. The samples from the hydrogen moderators at TS1 and TS2 were taken at the end of user cycle just before shutdown and initially tested with the thermal conductivity rig, then when the next user cycle started a couple of weeks later the measurements were repeated and compared to a neutron transmission measurement on the VESUVIO instrument.

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Annex IV.

CASE STUDY OF THE HANARO REACTOR, REPUBLIC OF KOREA

The cold neutron source (CNS) of HANARO is a good example of installation of a cold source at an existing research reactor. During the siting stage of HANARO, an appropriate area of land in the direction of the beam tube that looks at the CNS hole in the reflector region had been secured for a neutron guide hall building. The CNS hole is just beside the reactor chimney, and the in-pile section or vacuum container could be supported at the chimney wall. HANARO started its operation in 1995. The planning report for the cold neutron research facility (CNRF) project was carefully prepared and submitted to the government for review and eventually to Congress for budget approval in 2003. It was launched in July 2003 as a seven-year project. The scope of the CNRF project included the cold source, neutron guides, three new scattering instruments, and the relocation of three existing instruments from the reactor hall to the guide hall. The construction of the guide hall building was funded from a different budget than the CNRF project.

In preparing the planning report, communication between KAERI (the facility side) and users was key to carry out the planning. Prior to project planning, a feasibility study was performed by one of the users, a university professor, at the request of the government. The main investigation points of the feasibility study were whether the Korean neutron science community was ready to have cold neutrons and whether the CNRF would be well utilized to produce good science outcomes. This study conducted a survey including a questionnaire on the choice of scattering instruments to have. What was also included in this feasibility study report were letters of intent from users of universities, companies, and other neutron science facilities. The government review of this feasibility study was positive, and the government asked a science society for a project plan to be developed. The preparation of the project plan was, of course, strongly supported by KAERI and the user community. The contents of the project plan included social and scientific impacts of the facility, facility scope and specifications, and budget.

In the first stage of the project, the basic design of the cold source was started, the project investigator of each neutron scattering instrument was designated (3 KAERI staff and 3 university professors), and the international advisory group for this project was organized. Several experts from other facilities such as KURR, FRM-II, NIST, and OPAL were invited for consultation, which was crucial for this project. Based on the basic design report, an engineering company was contracted for the detail design of the cold neutron facility. A manufacturing trial of the moderator cell was performed, with which the full scale CNS mock-up experiment was performed. One of the key pieces of equipment for this mock-up experiment was a refrigerator which had been borrowed from KEPRI (Korea Electric Power Research Institute). The experience of the full scale mock-up experiment became the basis of the CNS operation. The manufacturing or purchasing of long-lead items such as a refrigerator and neutron guides needs to be well-defined at an early stage.

Hydrogen–oxygen interaction was the most important licensing issue. It has been shown by structural analysis that the vacuum chamber functions well as a pressure boundary even in the case of a hydrogen–oxygen interaction, so that no event in the CNS system could cause harm to the operating reactor.

Installing a guide cassette and replacing a beam plug was a challenging task in the sense that it was a high precision, high radiation work environment. The installation procedure had been

carefully checked, reviewed, and rehearsed. Installation of the in-pile section of the CNS into the reactor was the most important task. Since the CNS hole is open to the reactor pool water, the vacuum chamber needs to be close to the inner wall of the CNS hole in the beam direction in order to avoid the up-scattering of cold neutrons from the pool water film between. An out-of-pile test of this vacuum chamber installation was performed, and it was confirmed that the vacuum chamber was close to the inner wall of the CNS hole. The cold neutron flux is measured at the beginning of every cycle to check its consistency.

Arranging the facility to make it function as a user facility is very important for the efficient utilization and good outcome for neutron science. Operating a user office for scheduling and planning experiments and user convenience, preparing various tools and instruments for sample environments, and retaining prominent instrument scientists are essential for a user facility. Close interaction with the user group by fulfilling their needs in facility operation is a key factor to promote facility utilization. Regional (Asia and Pacific region) and international cooperation among facilities and users also causes global for use of the facility. To maintain the facility as national science infrastructure, it is very important to secure government funding for facility operation as well as research projects. In the meantime, sustaining public acceptance for using a research reactor as a neutron source for research in basic sciences and applications is becoming more important as there are more negative opinions of nuclear reactors.

Annex V.

QUESTIONNAIRE REGARDING THE LIFETIME, WASTE AND DECOMMISSIONING CONSIDERATIONS FOR COLD NEUTRON SOURCES AT RESEARCH NEUTRON FACILITIES

The following questionnaire was undertaken in 2019 with some facilities that had built cold sources in recent years.

1. *To which part of the neutron facility was the cold source attached and what kind of licensing or other regulatory issues had to be followed?*

   ANSTO: The CNS is located in the heavy water reflector as an integral part of the 20MW OPAL Reactor, thus under the reactor licence.

   PSI: SINQ and UCN are both spallation neutron sources. Both cold sources are part of the target stations. Due to the large amounts of deuterium we have to follow APEX rules which includes especially a strict double enclosure with the intermediate space monitored both for D_2 and oxygen. In addition, the leak tightness of the complete piping system had to guaranteed to be at least as good as 10^{-9} mbar l/s.

   TU Delft: The CNS will be installed as an experiment next to the research reactor core. It is attached to a support frame attached to the pool wall. It is positioned in front of the beam tube going to our experimental hall. Most of the CNS support systems will be housed in a separate building outside the reactor hall and outside the containment building.

   Regulatory issues. Initially a completely new nuclear operations license/full license revision was required by the national regulatory body. This was later reduced to a set of modification proposals for new instrumentation, penetrations through the reactor containment, containment isolation valves, modification of existing beam tubes, installation of the in pool assembly next to the reactor core. For the CNS support building a civil construction license procedure was followed.

2. *What was the expected operation and/or lifetime of the installed cold source?*

   ANSTO: Originally designed for 10 full-power (FP) years, now extended to 15 FP years.

   PSI: The expected lifetime of both our facilities was not clearly specified. For SINQ as a whole a lifetime of about 25 years was envisaged. Now the expectations are that we try to operate for at least 30 years. We've changed SINQ's cold source once. The present one is in operation since 2002.

   The situation with the cold source in our UCN facility is somewhat different because the total dose received by this vessel is negligible as compared to SINQ. The UCN facility is planned to be in operation for at least 20 years. A regular exchange of its cold source is not planned at the moment.

   TU Delft: The design lifetime is a minimum of 20 years.

3. *What was the real operation and /or lifetime of the installed cold source?*

   ANSTO: Replacement is scheduled for 2024, which will be the first replacement on design lifetime of 15 FP years.

   PSI: The present SINQ CNS is in operation since 2002.

   TU Delft: The CNS is not yet operational

4. *What reasons limited the operation/lifetime of the installed could source?*

   ANSTO: Lifetime of moderator chamber material under neutron irradiation, which is made of AlMg5.

   PSI: In SINQ the CNS was exchanged once in order to improve the cold neutron flux by introducing a re-entrant hole into the moderator vessel.

   TU Delft: The maximal thermal neutron fluence has been set to 7.79×10^{25} n/m^2 (20 years).

5. *What were the main operational problems happening during the operation of the installed cold source?*

   ANSTO: Multiple compressor and turbine failures due to design faults in the He refrigerator in the years 2006–2012. Faults were fully rectified by 2013. Near 100% reliability in 2013–2018.

   PSI: In case of UCN dealing with all three aggregation states of D_2 was a bit tricky in the beginning until we acquired sufficient experience.

   TU Delft: The CNS is not yet operational.

6. *How often did a replacement of the cold source occur?*

   ANSTO: First replacement scheduled in 2024.

   TU Delft: The CNS is not yet operational.

7. *What were the reasons for a replacement of the cold source?*

   ANSTO: Lifetime of moderator chamber material under neutron irradiation, which is $AlMg_5$.

   PSI: In SINQ the CS was exchanged once in order to improve the cold neutron flux by introducing a re-entrant hole into the moderator vessel.

   TU Delft: The CNS is not yet operational.

8. *What hampered the replacement of the cold source?*

   PSI: It is a very complex and expensive procedure to remove the CS. The activated CS is surrounded by two separate safety shrouds. It has to be done remote controlled and by using an exchange flask. Furthermore, the whole area has to be gas-tight sealed to avoid release of tritium.

   TU Delft: The CNS is not yet operational.

9. *What kind of regulatory and practical/technical issues had to be taken into account during the replacement of the cold source?*

   ANSTO: Replacement of the CNS is to be carried out in the reactor pool (to be drained during replacement). The biggest challenge is to control dose exposure to the active-handling staff, and at the same time avoid damage to the in-pool structures and components. There will be a limited time window of 4–6 months to minimise disruption to commercial production on the reactor. There is no major regulatory issue identified for this project.

   PSI: Apart from the topics mentioned in 8., leak testing and all other sorts of hands-on activities are complicated technical issues due to the restricted accessibility.

   TU Delft: The CNS is not yet operational.

10. *What kind of regulatory issues and practical/technical had to be taken into account during decommissioning the cold source?*

    ANSTO: There is no major regulatory issue identified for this project because the CNS itself is a Safety Category 3 component, i.e., no nuclear safety significance.

    PSI: Apart from the above mentioned topics the disposal of 20–30 m^3 of heavily tritium contaminated deuterium gas is an issue.

    TU Delft: The CNS is not yet operational.

11. *What kind of regulatory and practical/technical issues had to be taken into account concerning waste management of the cold source?*

    ANSTO: The final disposal of the CNS itself needs to be considered as part of the reactor decommissioning plan. Furthermore, over a long time the deuterium (moderator) inventory becomes tritiated. The final disposal of this tritiated inventory needs to be properly planned.

    PSI: The radioactive waste management is an important issue. The whole CS system has to be taken apart in a hot cell in order to separate different scrap materials (metals) which is a requirement from our licensing authorities for the ultimate waste storage.

    TU Delft: The CNS is not yet operational.

LIST OF ABBREVIATIONS

ANSTO	Australian Nuclear Science and Technology Organisation
ANVS	Autoriteit Nucleaire Veiligheid en Stralingsbescherming (Dutch regulator)
ATEX	Appareils destinés à être utilisés en ATmosphères EXplosibles
BARC	Bhabha Atomic Research Centre (India)
BRR	Budapest Research Reactor (located in Budapest, Hungary)
CANS	Compact Accelerator based Neutron Source
CARR	China Advanced Research Reactor (located in Beijing, China)
CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives (France)
CIAE	China Institute of Atomic Energy
CNBF	Cornell Neutron Beam Facility
CNEA	Comisión Nacional de Energía Atómica (Argentina)
CNS	Cold Neutron Source
CRP	Coordinated Research Project
CSNS	China Spallation Neutron Source (located in Guangdong, China)
DAC	Derived Activity Concentration
dpa	Displacements per atom
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
ENDF	Evaluated Nuclear Data File
ESS	European Spallation Source (located in Lund, Sweden)
FAT	Factory Acceptance Test
FRM II	ForschungsReaktor München II (located in Garching, Germany)
FWHM	Full Width at Half Maximum
HFBR	High Flux Beam Reactor (formerly located in Brookhaven, NY, USA)
HFIR	High Flux Isotope Reactor (located in Oak Ridge, TN, USA)
HFR	High Flux Reactor (located in Grenoble, France)
ILL	Institut Laue-Langevin (located in Grenoble, France)
ITP	Inspection and Tests Plan

J-PARC	Japan Proton Accelerator Research Complex (located in Tokai, Japan)
JINR	Joint Institutes of Nuclear Research (Russian Federation)
KAERI	Korea Atomic Energy Research Institute
LANSCE	Los Alamos Neutron Science Center
MDA	Minimum Detectable Activity
MTR	Materials Test Reactor
NIST	National Institute of Standards and Technology (USA)
OPAL	Open Pool Australian Lightwater (located in Lucas Heights, Australia)
ORNL	Oak Ridge National Laboratory (USA)
PE	PolyEthylene
PNPI	Petersburg Nuclear Physics Institute
PSBR	Pennsylvania State Breazeale Reactor (located in State College, PA, USA)
PSI	Paul Scherrer Institute (located in Villigen, Switzerland)
QA	Quality Assurance
QC	Quality Control
QMS	Quality Management System
SAT	Site Acceptance Test
SNS	Spallation Neutron Source (located in Oak Ridge, USA. Also, the former project name for the current ISIS facility, UK)
SSC	Structures, Systems and Components
TCNS	Texas Cold Neutron Source
TIG	Tungsten Inert Gas
TPCTR	Two-Phase Closed Thermosyphon with Reservoir
TRaM	Target, Reflector and Moderators
TS-1 (-2)	ISIS Facility Target Station 1 (2)
UCN	UltraCold Neutrons
VCN	Very Cold Neutrons

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