Design concepts for construction of cold neutron source

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Abstract
The cold neutron source (CNS) is a facility installed near the core to increase the cold neutron flux. The moderator material is limited from the reason of cross sections and build up of radiation damage, and in practice, the combustible hydrogen or deuterium is used in research reactors. Therefore we need to compromise and optimize between safety and a gain factor of cold neutron flux. We discuss generally how to draw up and promote the CNS construction project, considering safety-standard which is now admitted in many CNS facilities. Design concepts concerning neutronics calculation, commission procedures and material inspections are also discussed.

1. Introduction

The principal design criterion of the Cold Neutron Source (CNS) is a significant increase of cold neutrons at the experimental beam hole. However, the combustible hydrogen or deuterium is used as moderator and the CNS is installed near the reactor core. Therefore, we must optimize the engineering parameters for getting the maximum gain of the cold neutron flux with meeting safety criteria and requirements. We report firstly the guideline to draw up and promote the CNS project, and secondly the concept for the neutronics calculation, and then safety concept.

2. Design guidance of cold neutron source

For the CNS design, all relevant technical and scientific items and possible and/or required links to licensing procedure, manufacturer and independent experts (third party) should be implemented along the special guideline. The completeness of all items is important to make a good design from the high gain factor of cold neutron flux, safety, operation and scientific points of view.

Figure 1 shows us a possible guidance from Conceptual Design up to Operation Planning, the links to the licensing authority and, if required, to independent experts having experiences on CNS design in the last years.

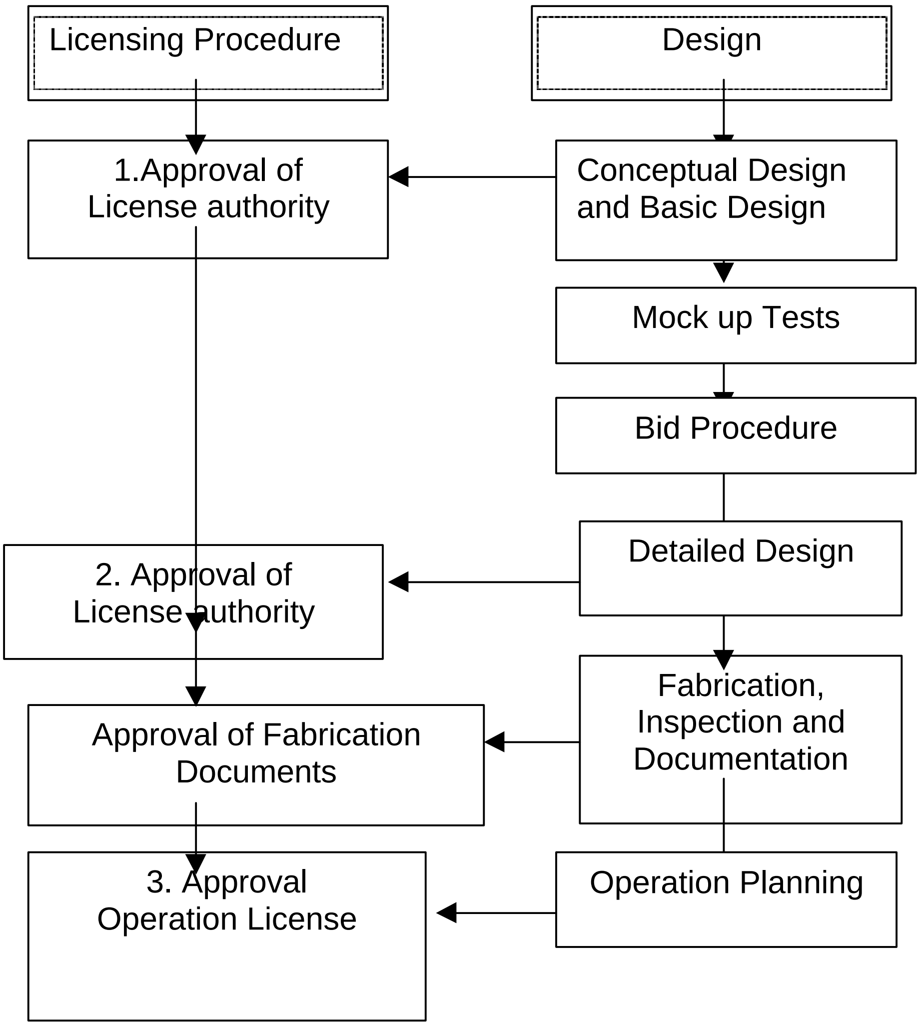

Fig. 1: Design guidance of cold neutron source.

For every step in the guidance, documents to find solutions for all questions and requirements must be prepared. These documents are used also to convince the licensing authority from safety point of view. These documents are listed up below along the design steps:

1) Conceptual design stage: the conceptual design document should include firstly the scientific effectiveness of the CNS installation from the material science and fundamental physics, and secondly engineering and safety design concepts with respect to the following items, (1) neutronics calculations: (1.1) neutron flux and gamma rays calculations in the reactor core and in the moderator cell, (1.2) nuclear heating estimation, (1.3) material choice of moderator, vacuum chamber including hydrogen cold loop which consists of the condenser, the moderator transfer tube and the moderator cell, and the moderator cell from neutronics point of view, (1.4) evaluation of moderator cell volume considering the total cross section of the cold neutron guide tubes for extracting cold neutrons with longer wavelength, (1.5) shielding calculations, (1.6) confirmation of theoretical calculations comparing with practical results of the other CNS facilities, (2) material selection and choice from viewpoint of engineering : (2.1) the material for the vacuum chamber and the hydrogen cold loop, especially for the moderator cell, should be investigated carefully to meet the demanded service conditions. For the hydrogen cold loop and/or for the moderator cell, there are four classes of well-established commercial Aluminium alloys that can meet the requirements. They are the 2xxxx series (AlCu), 5xxx (AlMg), 6xxx (AlMgSi) and 7xxx (AlZn). 5xxx and 7xxx are stronger but less ductile than 6xxx. The 2xxx and 7xxx have no well-established histories of use in a nuclear environment, and there are no examples for their use in cold neutron sources. The 5xxx and 6xxx alloys are the most widely used alloys in cold neutron sources, (see table 1), with the 5xxx class being the most popular. In case of aluminium alloy choice, it is necessary to check whether the CNS gets low or very high thermal fluencies and/or has an easiness of replacement. So intensive material investigation are necessary for composition, properties and limitation of the materials with respect to physical parameters, workability, mach inability, welding performance including radiation effects, cryogenic mechanical behaviour, radiation damage tolerance, aqueous corrosion tolerance, and the maximum service temperature, mechanical properties at low temperature, radiation effects at ambient and low temperatures, point defects and transmutation products due to irradiation, radiation hardening, tensile properties, fracture toughness, swelling, creep and stress relaxation under radiation environment. (3) effect estimation of the CNS installation from the reactor side, (4) safety evaluation of the in-pile part and auxiliary systems from the quality assurance point of view, (5) checking up of leakage effect if leakage process is required before rupture behaviour, (6) checking up licensing requirements and procedures, (7) first-stage system description of the CNS with design requirements: system description, functional description, instrumentation and control system description, location arrangement diagram, the descriptions of design and operation data and in-service inspection, (8) first-stage flow diagram of the total system, (9) first-stage local arrangement diagram in the building for the main components and the auxiliary systems.
2) Design and procedure of mock-up tests: establishing the scaling method for the mock-up test with respect to material, size of equipments and the mock-up test contents including heating up and cooling down ranges, and instrumentation, construction, estimation of the mock-up test results.
3) Detailed design stage: material specifications with material test sheets along the regulation standard as ASME, KTA codes, technical specifications for a in-pile part of CNS and auxiliary system, final material choice, embrittlement and the end of life behaviour for the planned operation years which are very important, heat transfer and stress calculation of critical parts of all load cases, leak concept before rupture including fracture mechanics calculation, first dimensional and stress analysis for critical load cases, fatigue analysis, investigation of the fabrication documents delivered from manufacturer, material procurement of special materials as Zircaloy [1], Aluminium and so on, final flow diagram of CNS, final system description, transient analysis of relevant load cases.
4) Bidding procedure: preparation of the detailed estimate (bid specification) for invitation of tender with all technical specification, review and comparison of the tenders for the order.

5) Final planning, manufacturing, inspection, testing: review of manufacturing documents, supplier rating, inspection of the fabrication steps, approval of the fabrication documentation, tests of special components if necessary.

6) Commissioning: preparation for the commissioning program, test plans, preparation of first operation manual.

7) Operation: preparion of final operation manual.

8) In-service inspection: preparation of in-service inspection plan, preparation of in-service inspection test procedures.

Table 1: Research Reactor based on Cold Neutron Sources and their Construction Materials

Reactor Type	Reactor Power (MW)	Thermal Neutron Flux (n/m²s)	Moderator	Moderator Cell Material	Vaccum Chamber Material
HFR ILL Grenoble	57	15×10^{18}	L-D_2	A5 Al (99,5 % Al)	Zircaloy-2
HFBR Brookhaven	60	3×10^{18}	L-H_2 subcooled	6061-T4 Al	
Orphee Saclay	14	3×10^{18}	L-H_2	A286 (Fe-26Ni-15Cr)	
FRJ-2 Jülich	23	$1{,}2 \times 10^{18}$	L-H_2 subcooled	Al-3Mg,F18	Al-3Mg,F18
DR3 Riso	10	7×10^{17}	H_2 supercritical	Al-3Mg	Al-3Mg
FRJ-2 Karlsruhe	43	5×10^{17}	L-H_2		
EL3 Saclay	17	5×10^{17}	L-H_2	Al-3Mg	
DIDO Harwell	15	4×10^{17}	L-H_2	Mg	
Herald Aldermaston	5	1×10^{17}	L-H_2 L-D_2	5056 Al (Al-5Mg)	5056 Al
JRR-3M Tokai	20		L-H_2	A286 (Fe-26Ni-15Cr)	6061Al
NBSR NIST	20	4×10^{18}	L-H_2	6061 Al	6061 Al
FRM-II Munich	20	8×10^{18}	L-D_2	6061 T6	Zircaloy-4
BER-II Berlin	10	3×10^{18}	H_2	AlMg3	AlMg3
KFKI Budapest	10	$2{,}5 \times 10^{18}$	L-H_2 subcooled	AlMg5	AlMg5
UCN Munich	20	8×10^{18}	D_2 5 % H_2	6061 T6 Al	Zircaloy-4

FRG2 Geesthacht	5	1,3 x 10^{18}	H_2 supercritical	AlMg3	AlMg3
RRR ANSTO	20	5 x 10^{18}	L-D_2 subcooled	AlMg5	Zircaloy
Hanaro Kaeri	30	5 x 10^{18}	L-H_2	AlMg5	Zircaloy
HIFAR ORNL	85	15 x 10^{18}	H_2 supercritical	6061 Al	6061 Al
KURRI Kyoto	5	0,2 x 10^{18}	L-D_2	5083 Al	5083 Al

3. Optimization of a cold neutron source

3.1. Choice of moderator

In table 1 all important CNS of the world are described with their main features. Many CNS uses liquid hydrogen as a cold moderator. The advantages of liquid hydrogen are obvious:

(1) The CNS moderator volume is small (typically, a few centimeter layer of liquid hydrogen is sufficient). This kind of CNS can be installed for example in a horizontal beam tube (HMI in Berlin).

(2) The nuclear heating of a small liquid Hydrogen CNS is small compared to a larger Deuterium source. The cooling power for such a hydrogen source is therefore also smaller compared to a deuterium source.

(3) A hydrogen source doesn't accumulate tritium (as it happens with deuterium) over the years. The hydrogen can be released into the environment without any problem when we need it.

(4) A deuterium CNS has a larger gain factor for cold neutron fluxes above 4 angstrom comparing with a hydrogen source [2]. The typical dimensions of a deuterium source are 30 – 50 cm in diameter with the same height of a hydrogen source. This large size is necessary, because deuterium has a mean free path one order larger than hydrogen. Deuterium CNS is suitable for a research reactor which has a heavy water reflector and many cold neutron guide tubes are required to be installed. The dimensions of a typical deuterium CNS allows us to install several guide tubes looking at CNS. A deuterium CNS, which is located at the maximum position of thermal flux in the heavy water reflector, would slow down more thermal neutrons to the cold neutron energy region. Therefore a deuterium CNS would be the first choice when one wants to do experiments with cold neutrons of longer wavelength than 10 angstrom and many cold neutron guide tubes are required.

The safety requirements for a deuterium CNS are comparable with a hydrogen CNS except for the safe enclosure of deuterium inventory with tritium. A deuterium CNS needs in general more cooling power than a hydrogen source because of large volume of moderator and thus it does cost.

3.2. Optimization of cold neutron source and neutron guide system (experiments)

In the beginning stage of the CNS plan, an intensive consulting procedure among the CNS, the neutron guide and the instrumentation group should occur. In the case of the FRM-II CNS the concept was to install <u>the light under-moderated deuterium CNS</u>. This can be achieved by reducing the size of the deuterium moderator. The advantage of this source is an overlap in the neutron spectra between thermal and cold neutron region. It is planed to mix some quantity of hydrogen into the deuterium in future in order to shift the neutron spectra of the CNS to longer wavelength region, when it does need.

3.3. Maintenance and reliability of a cold source

The availability of a CNS in a modern research reactor like the FRM-II is very important. The design of a CNS should therefore be optimized in such a way that the maintenance periods are short, and the reliability of this complicated technical system is high. In case of the FRM-II CNS the cooling down and warming up procedure is fully automatically controlled by the computer control system. This includes also the procedure for the cooling machine. The technical design should be made in a way, so that in case of a failure of a CNS component the time for replacing its component is short and easy.

4. Safety concept of research reactor cold neutron source

Now we have many cold neutron sources installed in the research reactors. And so, we have the design criteria of the CNS from a viewpoint of safety, which are reported already in many references [3,4,5,6,7,8]. The general concept admitted in most of CNS facilities including our concept is described in this section although it depends on the regulation standards of respective countries.

Basic concept for safety system design: (1) although CNS is installed close to the reactor core it is not considered a part of the reactor system from a viewpoint of safety. (2) The vacuum chamber surrounding the hydrogen cold system, which consists of the condenser, the moderator transfer tube and the moderator cell, is a pressure boundary for the reactor core. (3) The CNS should be designed to ensure that any event originating in CNS failure would not lead to loss of integrity of the reactor fuel, the reactor assembly and the reactor containment. (4) The CNS should be designed to ensure that any system failure should not lead to loss of the reactor

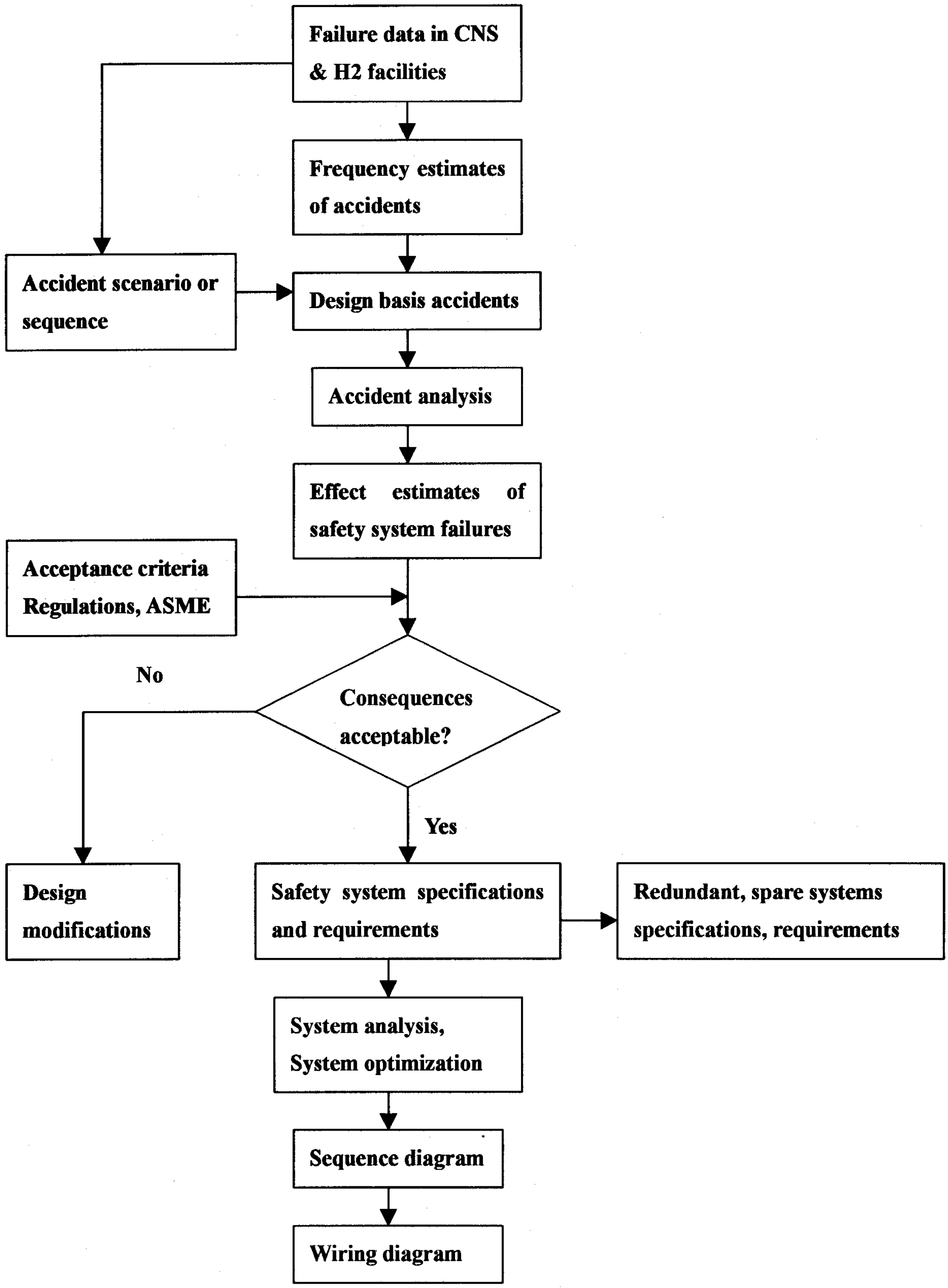

Fig. 2.Safety system design flow chart of CN

shutdown capability and damage to the reactor safety system.

1) For meeting the requirements mentioned above, we must firstly collect the failure data in CNS and hydrogen utilization facilities as shown in Fig. 2. Then we set up the design

basis accidents along the event scenario or sequence story considering the reasons of menacing CNS safety. (1) Safety system should have functions as hard wares not soft wares for protecting the reactor and personnel up to 100 % from the maximum design basis accident, (2) but furthermore we need to install the redundant and spare systems to supplement the main system when it doesn't function. (3) Hard wares for preventing the reasons toward accidents from developing, and mitigating the accidental effects should also be installed in the CNS facility. (4) Countermeasures to deal with accidents above the maximum design basis accident should be also installed. (5) It is necessary to train the operators to deal the accidents from a viewpoint of the risk management.

2) Next job is to establish the master logic diagram for the safety control system involving links to the reactor safety system.
3) Wiring system is designed along the master logic diagram.

Anyway, we should design the safety system conservatively considering the Murphy's law "If there is a possibility of several things going wrong, the one that will cause the most damage will be the one to go wrong".

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