Design Characteristics of the Cold Neutron Source in HANARO
Process System and Architecture Design

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Abstract.

The HANARO CNS adopts the liquid hydrogen as a moderator. The liquid hydrogen contained in the moderator cell evaporates due to gamma heating. The hydrogen vaporizes up to the condenser, where it is re-liquefied then it returns down to the moderator cell. This thermo-siphon loop can only be established under the very low temperature environment, which requires a method for a thermal insulation. Therefore, the processing system of the CNS basically consists of a Hydrogen System, a Vacuum System, a Gas Blanketing System, a Helium Refrigeration System, and a Control System. The overall design concept of the CNS is to ensure that the reactor safety systems and the on-site personnel and equipment are not adversely affected by the hydrogen-oxygen reaction from the CNS. The safety design criteria of the CNS is a defence-in-depth approach that provides several means to avoid any accidental contact between the hydrogen in the system and the air. Therefore, the principles of a conservatism, simplicity, redundancy, fail-safe design, and passive safety features are included to design it with an enhanced safety and efficiency. This paper presents the design characteristics of the HANARO Cold Neutron Source and the architectural design related to the reactor building.

1. Introduction

The HANARO (High-flux Advance Neutron Application ReactOr) has been operated for 12 years since its initial criticality in February of 1995. The reactor power has been gradually increased to 30 MWth through out its service period. In order to enhance the utilization capacity of HANARO, a Cold Neutron Source (CNS) development project has been underway since 2003. The detailed design of the HANARO CNS was completed on October, 2006. The overall design concept of the CNS is to ensure that the reactor safety systems and the on-site personnel and equipment are not adversely affected by the hydrogen-oxygen reaction from the CNS. The safety design criteria of the CNS is a defence-in-depth approach that provides several means to avoid any accidental contact between the hydrogen in the system and the air. Therefore, the principles of a conservatism, simplicity, redundancy, fail-safe design, and passive safety features are included to design it with an enhanced safely and efficiency. According to the safety classification based on ANSI N51.1[1], the HANARO reactor assembly is classified as safety class 3.

A vacuum chamber including a moderator cell, which will be installed into the reflector tank of the reactor, is the highest safety class of the CNS components. As the vacuum chamber should maintain its integrity in the case of a hydrogen-oxygen reaction, it is defined as an ultimate pressure boundary in accordance with ASME Sec. III ND code requirements[2]; therefore, the safety class of the vacuum chamber including a moderator cell was classfied as safety class 3 the same as the highest class of HANARO. All the components and pipings except that which were classified as a non-nuclear safety class were designed in accordance with ASME Sec. VIII code requirements[3] and ASME B31.1[4].

The HANARO CNS adopts the liquid hydrogen as a moderator. The liquid hydrogen contained in the moderator cell evaporates due to a gamma heating. The hydrogen vaporizes up to the condenser, where it is re-liquefied then it returns down to the moderator cell. This thermo-siphon loop can only be established under a very low temperature environment, which requires a method for a thermal insulation. Therefore, the processing system of the CNS basically consists of a Hydrogen System (HS), a Vacuum System (VS), a Gas Blanketing System (GBS), and a Helium Refrigeration System (HRS). This paper describes the design characteristics of the HANARO Cold Neutron Source and the architectural design related to the reactor building.

2. Design Requirements

The purpose of the cold neutron source is to increase the available neutron flux delivered to the instruments in the cold neutron range from 4 to 12 Å. Optimization is to be based on the neutron brightness (/s/㎠/steradian/Å). The gain factor of the brightness for these wavelengths should be comparable to the existing cold sources of a similar geometry (～10 to 20 at 7Å). The cold source shall be optimized to maximize the yield of the neutrons with an energy less than 5 meV, in the direction of the cold neutron beam port. There should be no significant degradation of the thermal spectrum near the experimental holes as measured after the cold source installation. Installation and testing of the cold neutron source shall be scheduled so as to cause a minimal disruption to the existing reactor utilization programs[5]. The change in the reactivity due to the introduction or removal of the liquid hydrogen into or from the moderator cell shall be within the allowable limit specified in the safety analysis report for HANARO. Special measures shall be taken to ensure that any pressure shock or vibration due to an abnormal behavior inside the vacuum chamber shall not adversely affect the integrity of the reflector vessel or the reactor structure. Provisions shall be prepared to protect the moderator cell from overheating in the event of a cryogenic system failure or a loss of the moderator circulation.

The vacuum chamber was designed to be able to fill it manually with Helium gas to enhance the heat transfer from the moderator cell to the outside through the wall of the vacuum chamber. The Helium gas for the emergency flooding shall be maintained properly, namely pressurized, for a timely injection into the vacuum chamber. The radiation level in the reactor pool top area shall not exceed the reactor trip set point, 2.5 mR/hr during a normal operation of the cold neutron facility. Expected maximum releases of radioactivity from the cold neutron facilities when added to the routine HANARO gaseous releases shall not exceed the requirements of the HANARO Safety Analysis Report. In addition, radiation protection issues will be evaluated according to the as low as reasonably achievable (ALARA) principle. The leak rate of the reactor building shall be less than the existing allowable limit, 570 m^3/hr, even after the completion of the CNS installation. The HANARO Safety Analysis Report was revised to reflect the inclusion of the cold neutron research facilities. The licensing of the CNS through an amendment to the existing HANARO Safety Analysis Report was successfully approved on August, 2007.

3. Process System Design

The design concept of the CNS system is basically to prevent the possibility of an accident by the hydrogen-oxygen reaction. Although all the equipment and piping which contain hydrogen gas are surrounded by a blanketing gas such as the properly pressurized helium or nitrogen, air ingress into the vacuum area should be analyzed. This assumption was applied to the basic design accident for the HANARO CNS. The final goal of the HANARO CNS is to accomplish an efficient system, which is operated safely with regard to the reactor and its personnel. To realize the CNS, it was designed to meet all the requirements through out the engineering practice performed at KAERI. The system flow diagram from the detailed design works is presented in Fig. 1.

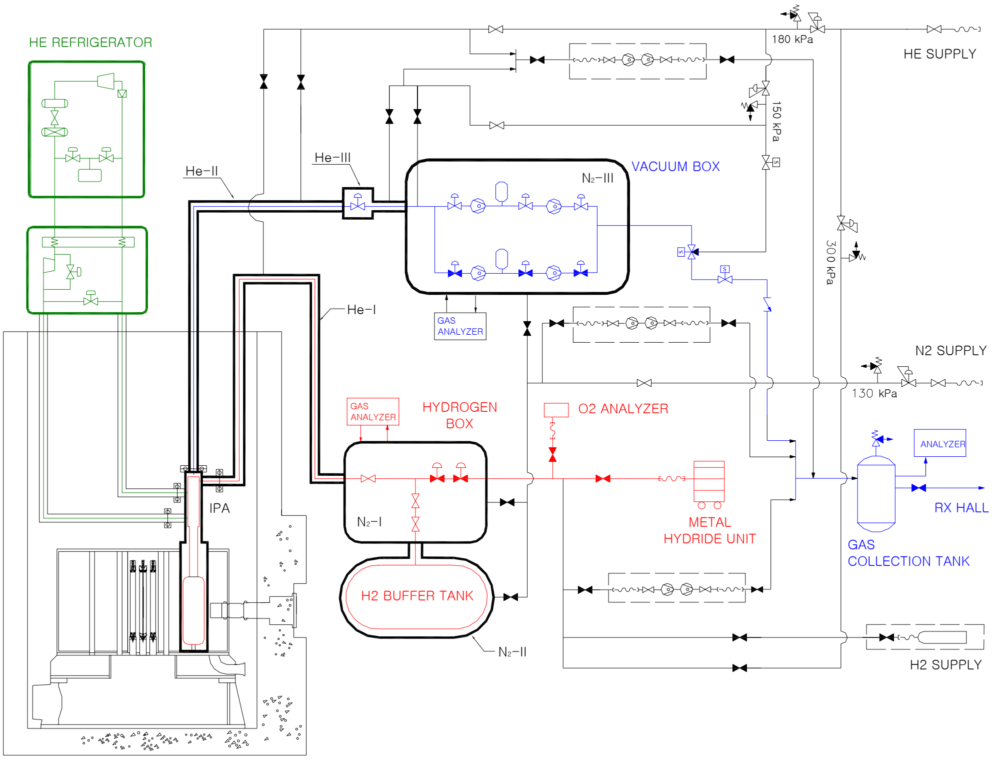

FIG. 1. Schematic Diagram of the HANARO CNS

3.1. Vacuum System

The Vacuum System (VS) is very important to securely maintain the required vacuum pressure in the vacuum chamber of the IPA. The main function of the vacuum system inside the vacuum containment is to act as a thermal insulation for the cold part of the in-pile assembly and to act as a safety barrier against the irruption of liquids and/or gases from the outside. The thermal insulation is of relevance to the performance of the in-pile assembly cooling. Gases and/or liquids that could enter the in-pile assembly would produce a frozen layer on the CNS thermo siphon loop surface which behaves as a vacuum cryopump. Pressure variations would not be detected, since all the liquids or gases are frozen, with the exception of helium. The irradiation of this uncontrolled layer could produce hazardous elements by a transmutation. Gas sampling and analysis during a CNS shutdown or CNS standby operation could serve to detect these elements.

The vacuum level for the cryogenic insulation shall be at least lower than 1×10^{-5} torr during the CNS normal operation[6]. The vacuum system makes a vacuum through two high vacuum pumping sets, one is on standby. The pumping set array is assembled with a set of valves, fittings and pipelines known as a vacuum manifold. They are assembled together in the vacuum box as shown in Fig. 1. The vacuum pumps discharge through the gas collection tank into the reactor hall. A pipeline called the main vacuum pipeline connects the vacuum pump sets and the manifold to the vacuum containment through the flange. This pipeline is surrounded with a helium blanket. If required, the vacuum containment can be filled with helium gas through the main vacuum line. The vacuum pumps and the manifold are placed within a box filled with helium gas. When the vacuum pumps are stopped, the exhaust pipeline is filled with helium through a filling valve to isolate the vacuum system from the air. And, a helium blanket surrounds the vacuum pipeline to the vacuum containment to isolate the vacuum system from the air and/or water. All of the VS is installed in a vacuum box filled with a blanketing nitrogen gas. The discharging gas from the vacuum pump is collected in a gas collection tank and then the collected gas is released into the reactor hall in the case of the hydrogen contact not being higher than 3.5% of the total volume.

3.2. Hydrogen System

The Hydrogen System (HS) consists of an In-Pile-Assembly (IPA) connected to the hydrogen buffer tank through adequate piping, a metal hydride unit, and a valve manifold. The IPA consists of a vacuum chamber, a moderate cell, a heat exchanger and a cryogenic transfer tube. The HS was designed with a completely closed loop concept to avoid a direct venting or its pressure relief. The HS is completely surrounded by blanketing gases to avoid any accidental contact with air or water from outside the system. The blanketing gas will be helium or nitrogen depending on the installation position. A part of the system in the reactor pool is filled with an inert helium gas and the other part is filled with nitrogen gas. The total hydrogen mass of the HS is less than 355 g. All gaseous hydrogen is safely accommodated by the hydrogen buffer tank of a 1.3 m^3 volume. The operating temperature is about 300 K at a warm condition and 21.82 K at a cold condition, while the operating pressure is 305 kPa(a) at a warm condition and 152 kPa(a) at a cold condition[7].

The HS is designed to be passively safe, simple to operate, and require little maintenance, and minimizing a gas handling. There is no credible scenario in which the reactor or the reactor building can be damaged by an accidental release of hydrogen. Components belonging to any of the multiple hydrogen boundaries inside the reactor building shall be seismically qualified or shall be shown by a analysis to maintain the hydrogen containment integrity of the HANARO SSE response spectrum. Very high purity hydrogen gas shall be used in the cold neutron source to preclude an oxygen contamination of the primary hydrogen system. There are two different design pressures for the components of the hydrogen system. The vacuum chamber as a safety barrier must maintain its structural integrity even at the worst design basis accident. The design pressure of the vacuum chamber shall be 3000 kPa. On the contrary, an internal part, like the moderator cell, does not require such a high design pressure. The hydrogen boundary is designed so that it can maintain its integrity against the maximum operating pressure. Adding some margin to the maximum operating pressure, 305 kPa(a), the design pressure of the moderator cell, connecting pipes and valves and the inner vessel of the hydrogen buffer tank has been determined as 500 kPa(a). Fig. 1 shows the different applications of the design pressure to be applied to the hydrogen boundary. It is said that the outer-most barrier of the system schematics shall have a design pressure of 3000 kPa to properly act against the worst design basis accident.

3.3. Helium refrigerator System

The HRS is intented to cool down and liquefy the gaseous hydrogen to a sub-cooled state in the condenser in order to establish a thermo-siphon. The HRS must remove the heat load which is imposed on the condenser through the thermo-siphon. The HRS has two different operating capacities for both the CNS and the Deuterium CNS, which will be added in the future. The HRS is being designed in accordance with the following operating conditions, 1500 watts at 14 K for the CNS and 2000 watts at 19 K for the Deuterium CNS. The VS is to act as a thermal insulation for the cryogenic part of the IPA and act as a safety barrier against an irruption of liquids and / or gases from the outside. The thermal insulation is of relevance to the performance of the IPA cooling system process. The operating mode is closely inter-related with the operation status of both the cold neutron source and the reactor. The reactor or cold neutron source is not able to operate without a normal operation of the HRS. Table 1 shows the relationship between the HRS and CNS related to a reactor operation[8].

Table 1. Relationship between the HRS and CNS related to a Reactor Operation

HRS	CNS	HYDROGEN	REACTOR
OFF	SHUTDOWN	GASEOUS	SHUTDOWN
COLD	START-UP	LIQUID	SHUTDOWN
	NORMAL	LIQUID	OPERATION
WARM	SHUTDOWN	GASEOUS	SHUTDOWN

4. CNS Equipment Island

The systems and components for the cold neutron research facility are located at 4 different places based on their dedicated functions. While the in-pool assembly is located in the reactor pool, the helium compressor station will be placed in the auxiliary building outside the reactor building, by considering that it produces a vibration and a big noise during an operation. The remaining parts, which have a limitation in the length of their connecting pipe for the required performances, shall be installed in the CNS Equipment Island (CEI) in the reactor building. The hydrogen buffer tank, vacuum pumps and valves, helium cold box and instrumentation and control systems etc., are accommodated in this CNS equipment island. As shown in the figure 2, the CEI will be located in the north-west area of the reactor building.

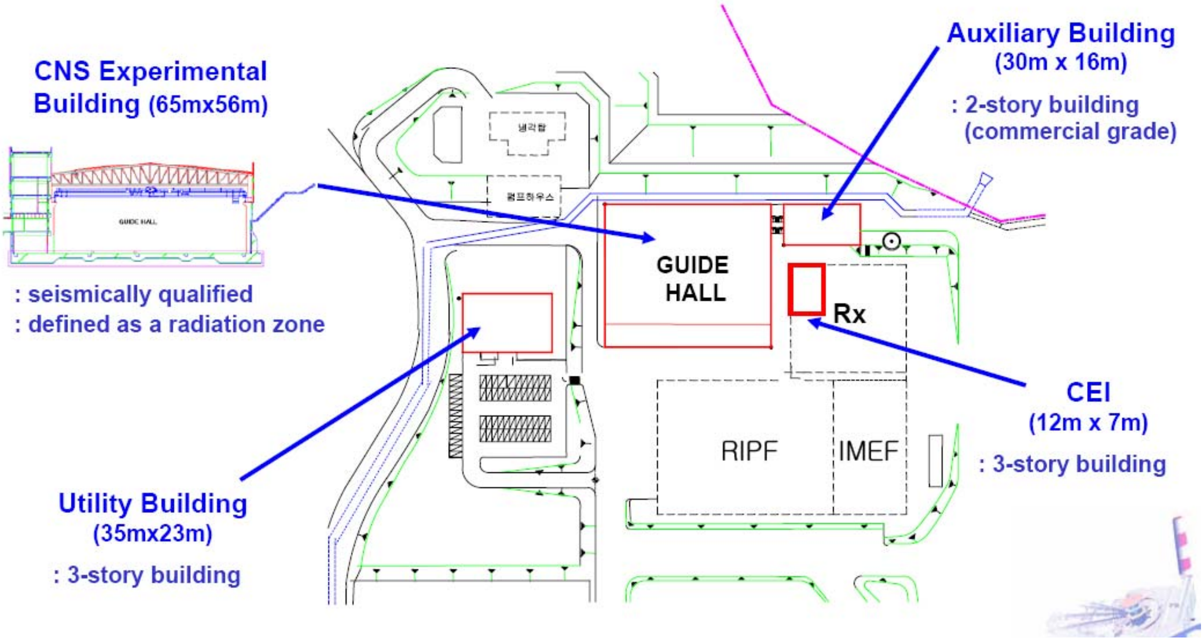

FIG. 2. Cold Neutron Research Facilities at HANARO Site

The CEI was designed to be a 3-story rahmen structure. The ground floor is reserved for the guide shielding room for accommodating the neutron guide system. This room will be made of a heavy weight concrete, higher than 3.5 g/cc in its density. The neutron guide installs to the neutron guide hall to be located in the direction of the north-west side of the reactor building. It penetrates through the reactor wall of the west side so it interfaces with the CEI at the ground floor. There should be good enough space for the shielding as well as maintenance of the neutron guide facilities at the ground floor. The second floor will be occupied by instrumentation and electrical equipment. The most critical devices for the CNS operation, such as the cold box, hydrogen and vacuum components shall be located in the third floor of the CEI[9]. A few pipelines connected to the IPA will be routed into the CEI and connected to the pumps, tanks or valves installed there. As shown in Fig. 2, the CNS equipment island is apart from the reactor pool side. It is required that the vacuum pump should be placed as close to the in-pool assembly as possible to assure the evacuation performance of the vacuum pumps. In addition, the pipeline between the IPA and the hydrogen buffer tank should be routed as short as possible to lower the possibility of a hydrogen leakage. In view of this basic requirement, the equipment layout along the structure is designed as shown in Fig. 3.

Pipelines, which are classified as seismic category II, will be installed from the CNS Equipment Island (CEI) into the reactor pool. There are so many interfaces to be considered between the new design and the existing structures in the reactor building. First of all, it is required to establish a proper pipeline layout to connect the hydrogen buffer tank to the moderate cell and the vacuum pumps to the vacuum chamber of the IPA to be installed in the reactor pool. Both the hydrogen transfer line and the vacuum evacuation line should maintain their structural integrity to avoid any hydrogen gas leakage from their pipelines. Of course, they were designed to have double wall pipes filled with blanket gases either helium or nitrogen by means of a defense in depth approach. To obtain a better layout of the pipelines, it was decided to use the support floor to be connected to the side wall of the reactor concrete and to make a new support floor. There is no way to accommodate the space for the vacuum box and its pipelines but to have embedded steel plates around the reactor outside wall. So, several existing equipment and supports such as the cable trays, HTS support, and pipeline of the hot water layer system shall be moved or replaced in the reinforced structural members. It is intended to share the embedded plate to install the new equipment.

The CEI was classified as a non-nuclear safety (NNS), seismic category II and quality class T. The CEI should be seismically qualified for SSE response spectrum according to its seismic class. And, the CEI was designed to optimize the interferences with the existing structures or facilities in the reactor hall. An appropriate height and space of each floor were reflected for the structural design to avoid any problem in installation or maintenance work. The ground floor occupied by the concrete shielding should have an enough space to maintain the primary shutter of the neutron guide system. Appropriate airflow to ensure a rapid hydrogen/air mixing and transportation is provided in the rooms containing a hydrogen tank or lines. The third floor shall be designed as a fire-free zone. Physical barrier or proper measures shall be provided to block a propagation of any fire originating outside into the room for the hydrogen equipment.

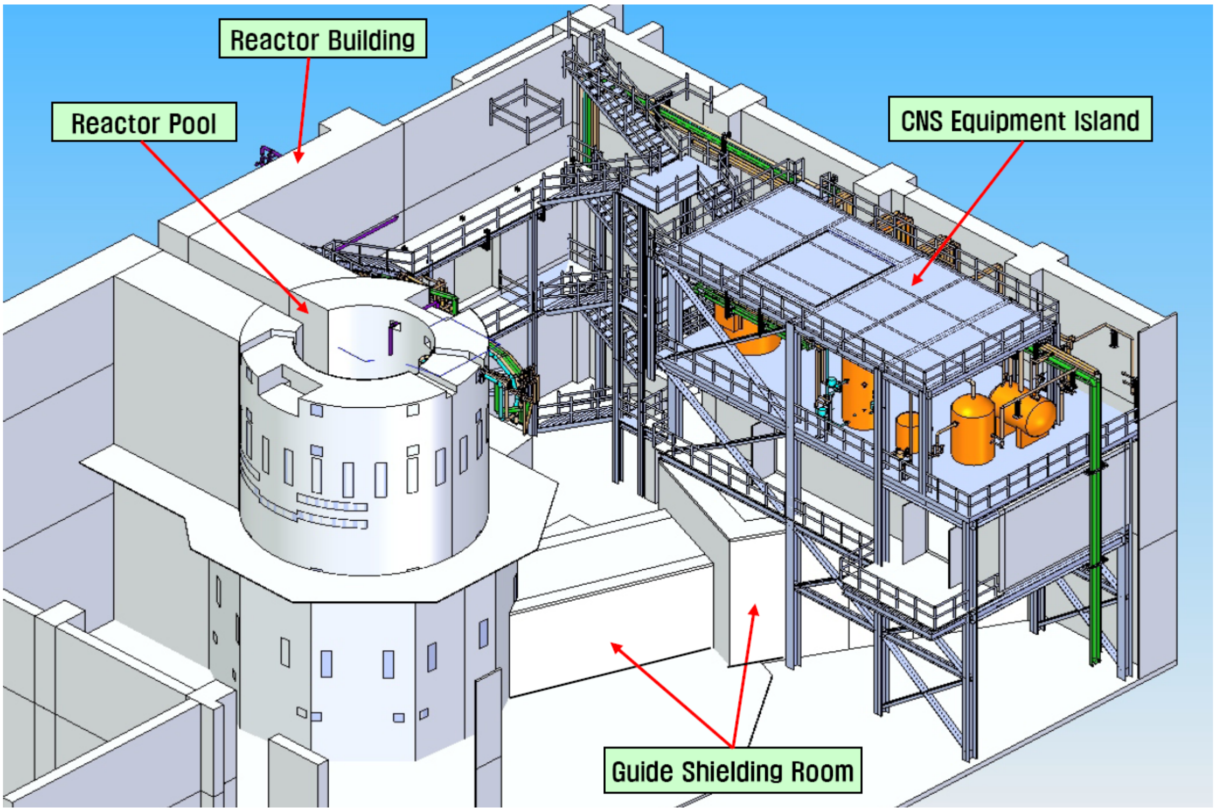

FIG. 3. CNS Equipment Island (CEI) and Reactor Pool

All the hydrogen components will be installed in the third floor of the CEI. The hydrogen boundary will be enclosed by a gas blanket as a concept of a double barrier to block the possibility of a hydrogen-oxygen reaction. Nevertheless, it may have to be assumed that hydrogen could be leaked out and mixed with air, by a double failure such as a break by some impact, then a deflagration or fire could occur in the room. Based on this scenario, the room may have to be opened widely to the air to reduce the possibility of a hydrogen cloud in a small confined space. It may minimize the degree of a fire. On the other hand, a fire caused by the conservative scenario mentioned above spreads easily in the reactor hall if the room is not physically isolated. Another concern is that a fire originating outside the room must not be transferred into the hydrogen equipment in the room, which may increase the internal hydrogen pressure. To avoid the fire propagation to the room, a physical isolation of the hydrogen equipment room should be required. Considering the situation stated above, it could be a possible that the equipment room is designed as a fire-free zone with a physical protective wall, on the condition that a well-reviewed ventilation system for the room shall be provided.

5. Cold Neutron Laboratory Building

The project for the Cold Neutron Laboratory Building (CNLB) started in January, 2004 and now it is under construction of about 60 %. The CNLB construction work will be completely finished in May, 2008. There are two cold neutron-related buildings except for the CNLB. The first one is the auxiliary building which is located to the north side of the reactor buildin as shown in Fig. 2. The compresseor and the cooling water system for the helium refrigerator shall be placed in the building around January 2008. It is expected that the helium refrigerator will be supplied to KAERI after it finishes its the factory acceptance test to be scheduled in January 2008. The second one is the utility building to accommodate the main electrical power system.

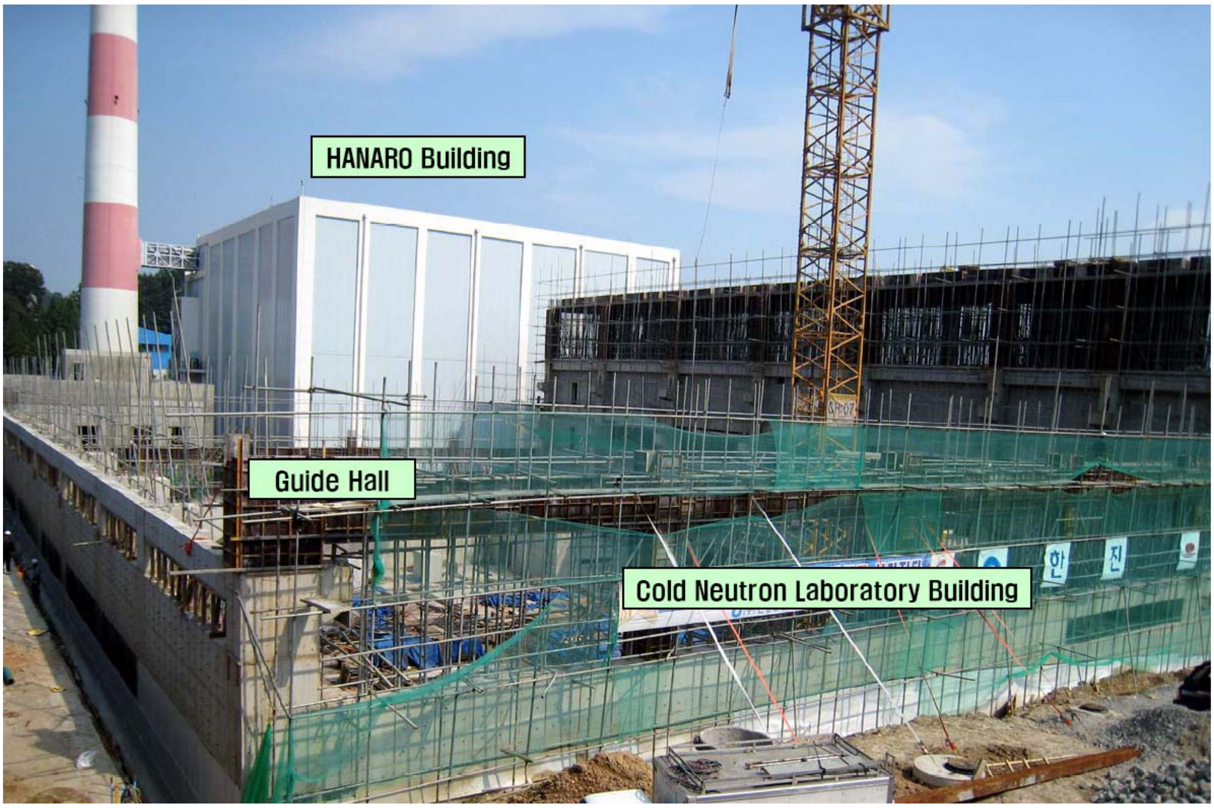

FIG. 4. Construction Status of Cold Neutron Laboratory Building (7th, September)

The CNLB is being installed near the existing reactor building in HANARO which has being operated since its initial criticality in February of 1995. Therefore, it is required to maintain the structural integrity of the reactor building during any cases related to design earthquakes. When a design earthquake is occurring, the CNLB is securely prevented form some kinds of its structural collapse or uncontrolled displacement caused by a dynamic response. That's why the CNLB is classified as seismic II category conforming to the design spectrums of a Safe Shutdown Earthquake (SSE). Considering a seismic interference, the CNLB was designed to have a seismic gap of 50 mm in distance between it and the reactor building, under-ground. The guide shielding room, which contains the neutron guide, is connected from the reactor building to the guide hall. The guide hall does not contain any radiation source inside. However, when the reactor is in operation and the neutron guides are opened, there is a possibility of a radiation risk in the guide hall. For this reason, the guide hall shall be classified as a radiation zone. It does not have any special licensing requirements connected to the nuclear safety. The licensing was established based on the radiation protection and building integrity points of view. The licensing of the CNLB was approved in April, 2006.

6. Conclusion and Future Works

The purpose of the cold neutron source is to increase the available neutron flux delivered to the instruments in the cold neutron range from 4 to 12 Å. The essential needs of the user groups is to obtain a maximum gain in the cold neutron flux and a good operational reliability. The governing safety aspects will be the reactor safety, the personnel safety, and the facilities protection against damage. The most important factor for the safety design criteria of the cold neutron source is a defense-in-depth approach that provides several means of avoiding any accidental contact between the hydrogen and air and also provides the means to mitigate a hydrogen release, given that an accidental release is assumed to occur. Therefore the safety of the cold neutron source facility is being guaranteed by multiple approaches. Adequate conservatism is being given to the design of the liquid hydrogen boundaries to ensure a high integrity boundary. Major safety considerations are concentrated on a hydrogen safety and radiation safety. The detailed design based on the safety criteria and user's requirements was completed in October, 2006 and it will provide the basis by which the manufacturing, installing, and commissioning of the CNS proceeds. All of the CNS equipment and systems except for the IPA will be installed from in May, 2008 and it will start its commissioning from the end of 2008. The IPA will be installed in the first half of 2009. Finally, it is expected that the cold neutron beam will be available from the beginning of 2010.

ACKNOWLEDGEMENTS

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