CNS In-Pool Assembly Mechanical Design for OYSTER Project

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ABSTRACT

The Cold Neutron Source (CNS) facilities consist of utility systems such as helium refrigerator system, hydrogen supply system, vacuum system, gas blanket system and CNS In-Pool Assembly (IPA). The main function of IPA is to moderate the thermal neutron beam created in the reactor in a layer of cryogenic liquid hydrogen (about 22.9 K), and it is located close to the reactor core to maximize the cold neutron production. It requires an advanced design technique such as high-degree vacuum technology to maintain the liquid hydrogen in the moderator cell of the IPA during normal operation. In addition, a robust and reliable design is essential from a safety perspective because the IPA deals with liquid and gaseous hydrogen. The most important safety design requirement of the IPA is to minimize the possibility of hydrogen gas leakage and ingress of oxygen and air from outside, and to withstand the blast pressure when a hypothetical hydrogen explosion occurs even though its possibility is extremely low.

1 Introduction

The Reactor Institute Delft (RID) of Delft University of Technology (TU Delft) is a knowledge centre on nuclear topics. It operates a 2.3 MW research reactor (HOR: Hoger Onder-wijs Reactor), irradiation facilities and laboratories, and its neutron and positron instruments. The OYSTER project (Optimized Yield - for Science, Technology and Education - of Radiation), co-funded by the Dutch government, TU Delft, and a number of commercial parties, is under progress to expand the potential of the research reactor by improvements and expansions of the RID infrastructure. The installation of the Cold Neutron Source (CNS) is one of the main items in this project. The function of the CNS is to let the neutrons from the core pass the liquid hydrogen (about 22.9 K) and increase the intensity of low-energy neutrons, which is called a cold neutron, to enlarge the applicability of neutrons in various fields of research. The RID has chosen the thermo-siphon type CNS suggested by the KHC (KAERI-Hyundai Consortium, Republic of Korea) in 2014. The basic operating scheme is similar to the HANARO CNS, which is now running by KAERI. The basic design has been completed and the detailed design and fabrication is now underway. The CNS facility consists of the In-Pool Assembly (IPA) and utility systems such as a helium refrigerator system, vacuum system, hydrogen supply system, and gas blanket system. The IPA is one of main equipment of the CNS facility. It moderates the thermal neutron beam with cryogenic liquid hydrogen in the moderator cell to produce the cold neutrons. The design of the IPA shall be very careful from safety point of view because the IPA is usually installed close to the reactor core and it deals with liquid or gaseous hydrogen, which might cause a hypothetical hydrogen explosion even though its possibility is extremely low. In this paper, the basic design concept of the IPA to ensure structural integrity under the most severe credible accident is described from a mechanical point of view.

2 IPA mechanical design

2.1 Operating principle of thermo-siphon type CNS

The working principle of a thermo-siphon type CNS can be simply stated as a natural circulation phenomenon, which is driven by the density difference between the liquid and gaseous hydrogen. When the liquid hydrogen in the moderator cell is heated by the neutron and gamma ray from the reactor core, it evaporates and goes upward into the heat exchanger of the IPA, and the heat exchanger liquefies the gaseous hydrogen again. Then, the liquid hydrogen flows down to the moderator cell by gravity. This natural circulation occurs inside of the IPA and continues during normal operation. Figure 1 depicts the basic thermo-siphon phenomenon occurring in the IPA.

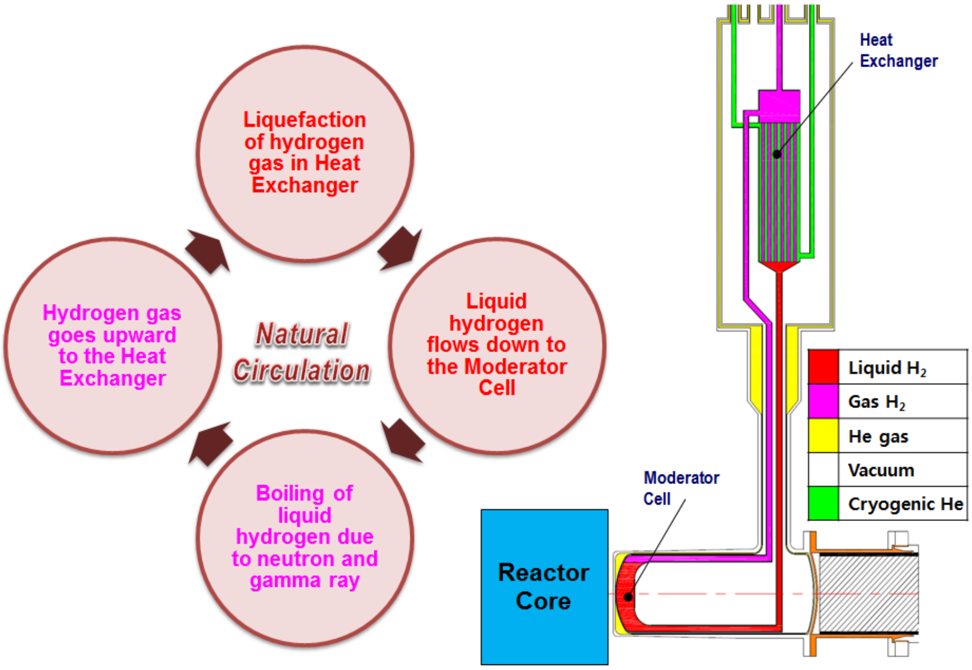


Figure 1 Schematic drawing of thermo-siphon

2.2 Basic design concept for IPA

One of the most important technical issues when it comes to the design of the IPA is how to minimize the possibility of a hypothetical hydrogen explosion. This accident is the most severe event that can be occurred in the IPA. To meet this requirement, the IPA adopts the triple containment design concept from a safety point of view, as shown in Figure 2. The first containment is the heat exchanger, moderator cell, and the hydrogen transfer pipes that connect the heat exchanger and moderator cell. These parts contact directly with hydrogen and experience large thermal deformations owing to a temperature change between the shut-down and normal operation conditions. The second containment consists of the vacuum chamber, which encloses the moderator cell, the vacuum housing containing the heat exchanger, and the vacuum transfer pipe. The third containment of the IPA is formed from a helium containment vessel, helium housing, and helium transfer pipe. The second containment makes a vacuum space to maintain the cryogenic liquid hydrogen within it by minimizing the heat leak from outside, and acts as a physical barrier against hydrogen leakage. The third containment is the outermost component that shall withstand the blast load as a third physical barrier if the hypothetical hydrogen explosion occurs. This last containment shall confine all adverse effects from various loadings under normal, abnormal, and any accident cases to protect the reactor and reactor structures installed in the reactor pool. The space between the inside of the third containment is filled with helium gas. This blanketing gas itself is not directly connected to the safety function, but acts as an important protective barrier, of which the pressure can be easily monitored. Therefore, if a failure occurs on the containments, the monitoring system can detect it immediately. The vacuum state inside the second containment is also monitored to detect any leaks before a break of the containment.

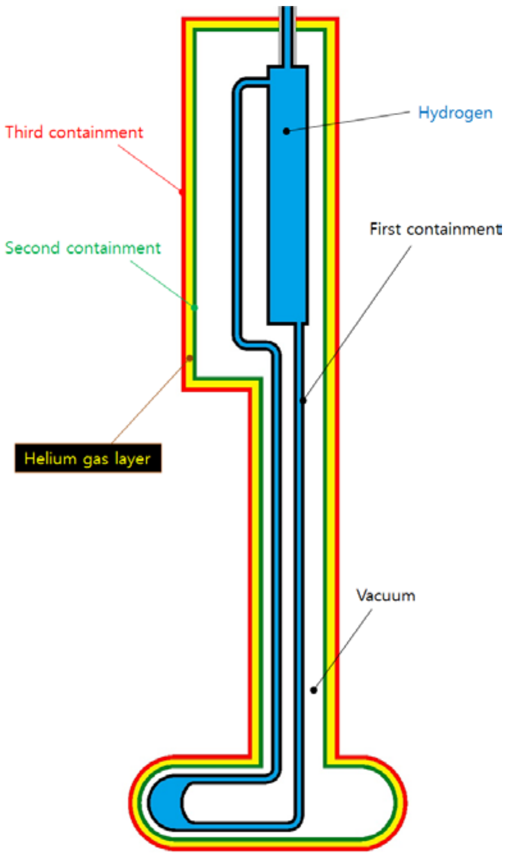


Figure 2 Triple containment design concept

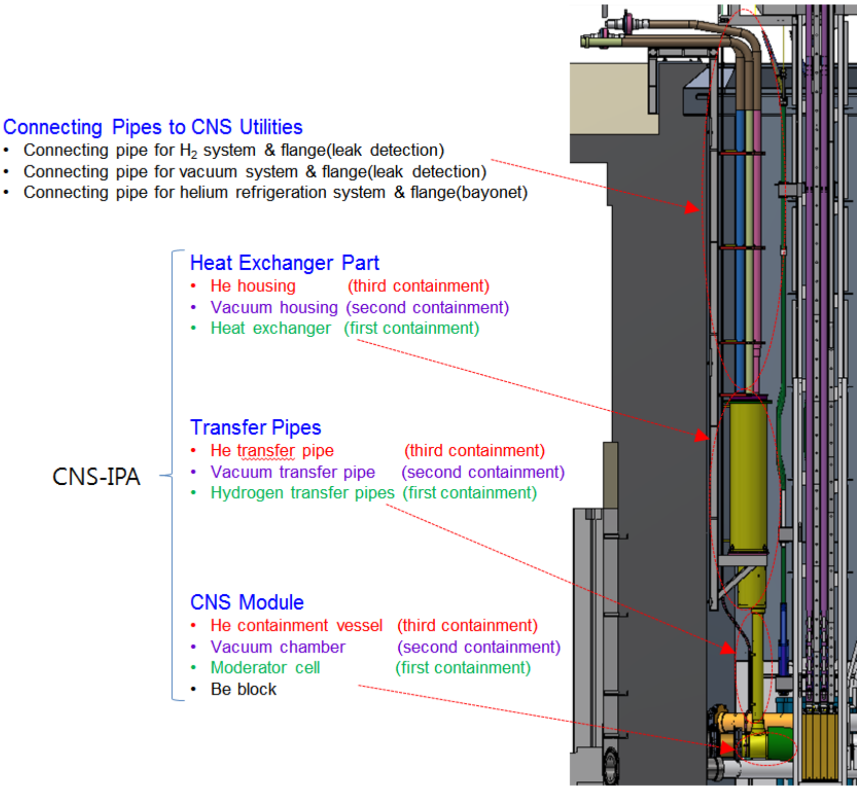


Figure 3 General arrangement of IPA

2.3 Safety philosophy and relevant Codes and Standards for IPA

The safety classification of the OYSTER project is based on the current HOR classifications. HOR has three safety classes as shown below:

(a) HOR SC1
All SSCs that are related to the process safety (protection and control process) and containment (limitation of consequences, serious mal-functions).

(b) HOR SC2
All SSCs that secure the safe functioning of the SSCs in HOR SC1, or that form a second line of defense on a lower hierarchical level, or have a lower ranking in relation to process safety.

(c) HOR SC3
All SSCs that are necessary for normal functioning, maintenance, and use of the reactor installation.

(d) HOR NNC
All non-nuclear SSCs that are not related to safety and are not classified as HOR SC1, SC2, or SC3.

The quality class is designated to design, fabricate, install, and test the safety related structures, components, and systems in accordance with the standards that are appropriate for their intended safety function. The quality classification is generally consistent with the safety classification, but there can be some deviations even within a similar safety classification according to the difference between the various functions of the pressure retaining wall or components. There are three (3) quality classes for the CNS: QC1, QC2 and QC3.

(a) QC1 shall conform to all requirements of the ASME NQA-1 or its equivalent.
(b) QC2 components shall satisfy the KHC QAM based on the ASME NQA-1 or ISO 9001. However, the items classified into QC2 do not follow the ASME NQA-1 fully such as the QC1 items. The detailed requirements to be satisfied are described in KHC QAM.
(c) QC3 is applied to the HOR SC3 components. Basically, QC3 components shall satisfy the KHC QAM based on the ASME NQA-1 or ISO 9001. However, the requirements of the ASME NQA-1 that the components classified into the QC3 shall meet are less than the QC2 components. A detailed description is also given in the KHC QAM.
(d) Non-QC is applied to the NNC components. There is no specific QC program, but the manufacturer conforms to well-accepted industrial standards or the manufacturer's quality program.

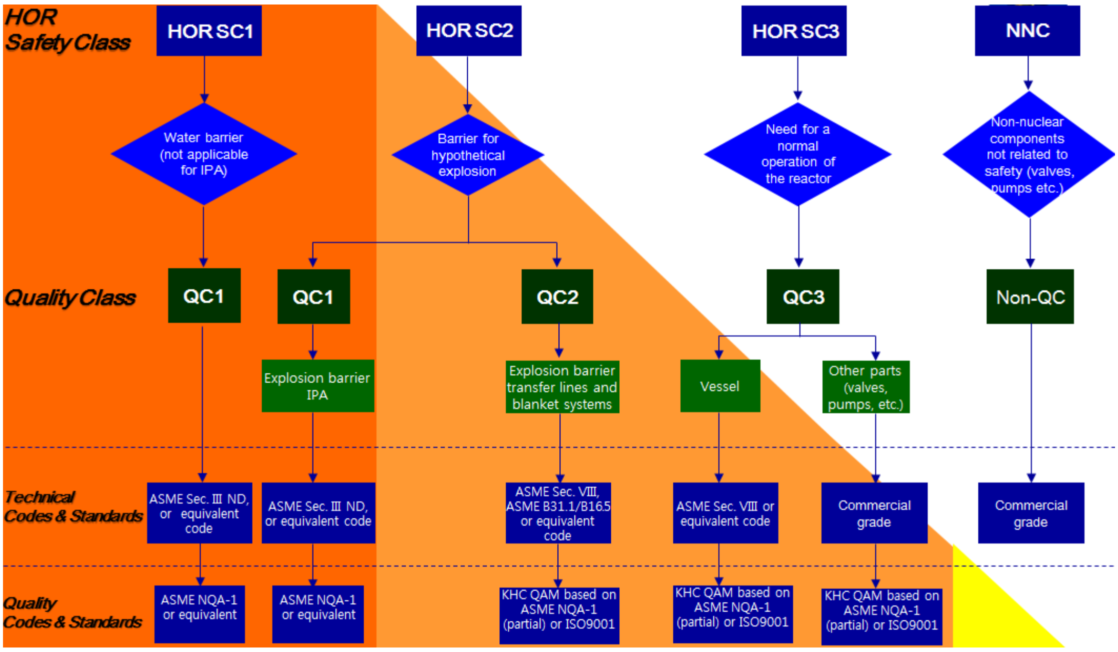


Figure 4 Safety Class, Quality Class, and Codes and Standards for OYSTER Project

Bascially, the safety class of the IPA is classifed into "HOR SC2," but the quality classes for each component are different depending on their functions and importance from a safety point of view. The outermost components (the third containment) such as the helium containment vessel, helium transfer pipe, and helium housing have the highest level of quality class (QC1) because they have to withstand the hypothetical hydrogen explosion which is the most severe credible accident.

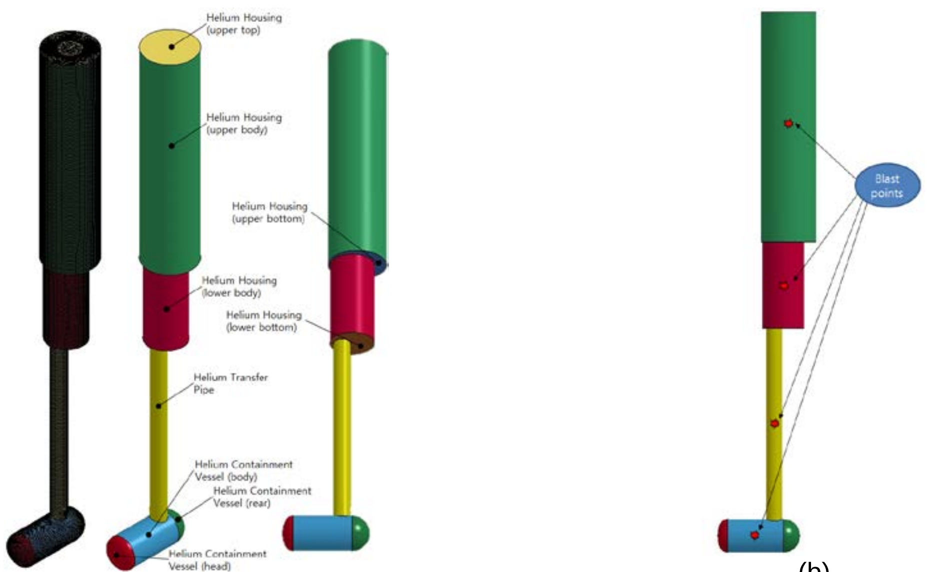
The Codes and Standards are carefully selected and designated based on this safety and quality classification, as shown in Figure 4. The ASME Codes and Standards are applied to the construction of the IPA. The highest code class is designated to the components of the third containment because of the importance of safety [2]. The other major components are constructed according to the relevant codes and standards, as shown in Table 1.

Table 1 Codes and Standards for major components of IPA

	Major Components	Safety Class	Quality Class	Codes and Standards
CNS Module	Moderator cell	SC3	QC3	ASME Sec. IIIV, Div.1 [1]
	Vacuum chamber	SC2	QC2	ASME Sec. IIIV, Div.1
	Helium containment vessel	SC2	QC1	ASME Sec. III ND [2]
	Beryllium block	SC2	QC2	N/A
Transfer Pipes	LH_2 transfer pipe	SC3	QC3	ASME B31.3 [3]
	GH_2 transfer pipe	SC3	QC3	ASME B31.3
	Vacuum transfer pipe	SC2	QC2	ASME B31.3
	Helium transfer pipe	SC2	QC1	ASME Sec. III ND
Heat Exchanger Part	Heat exchanger	SC3	QC3	ASME Sec. IIIV, Div.1
	Vacuum housing	SC2	QC2	ASME Sec. IIIV, Div.1
	Helium housing	SC2	QC1	ASME Sec. III ND

2.4 Assessment of structural integrity of IPA

One of the critical issues in the assessment of the IPA was a hypothetical hydrogen explosion because this is the most severe accident that envelopes all other credible events. A reasonable and acceptable method shall be used to verify that the IPA can withstand the blast pressure, and an explosion accident does not cause damage to the reactor safety. The maximum allowable explosion pressure of 30 bar (a) that the IPA shall withstand was obtained by the analytical methods and the blast simulation results. The geometry of each component of the third containment of the IPA was determined to have sufficient safety margins based on these results.



(a) (b)

Figure 5 Finite element model and blast points for the simulations

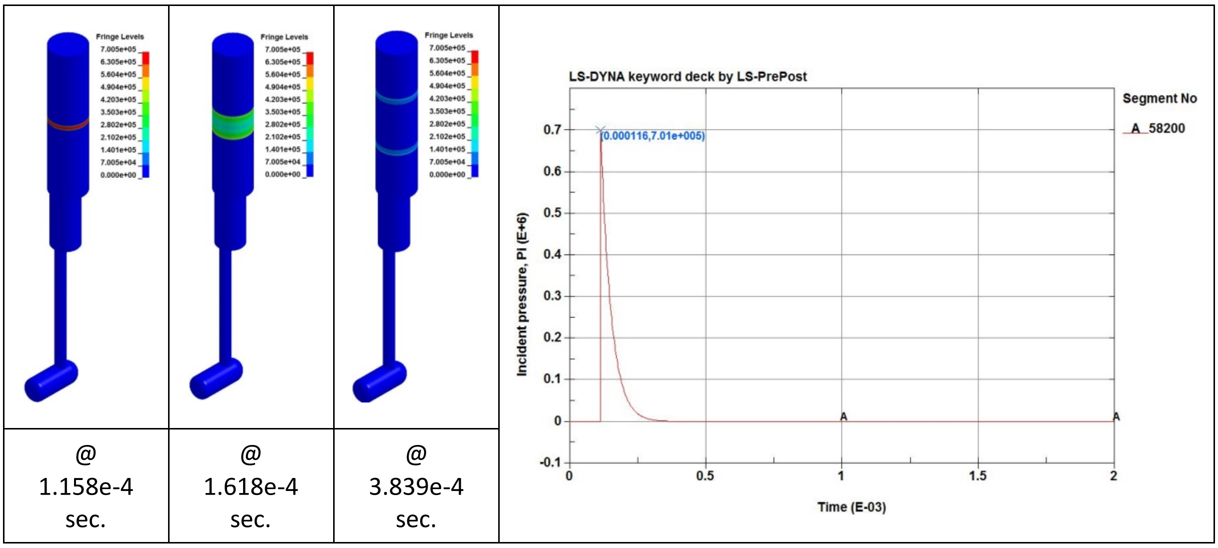


Figure 6 Incident pressure wave contour and history plot (helium housing upper)

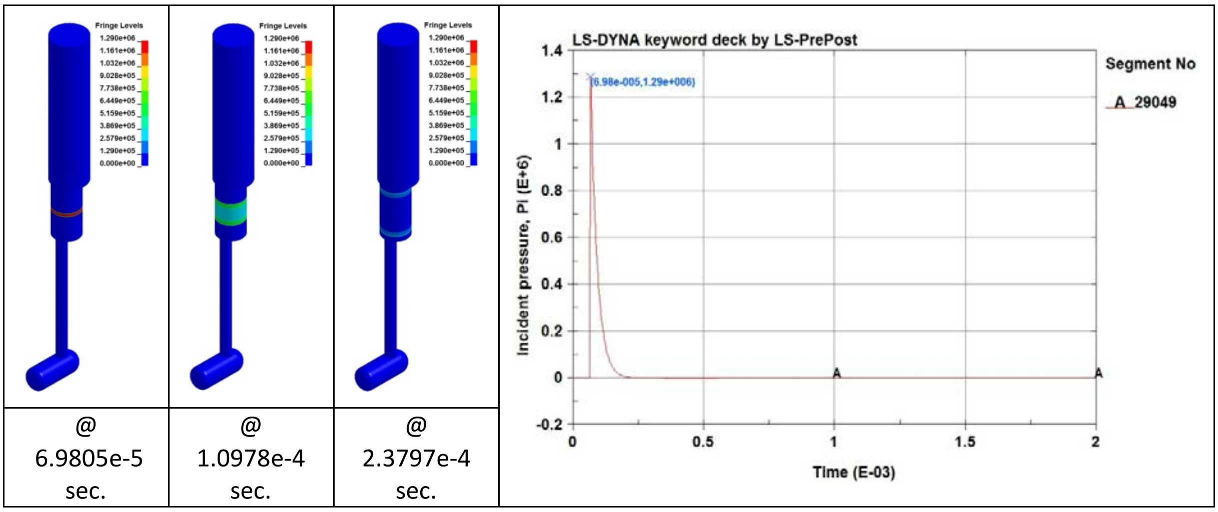


Figure 7 Incident pressure wave contour and history plot (helium housing lower)

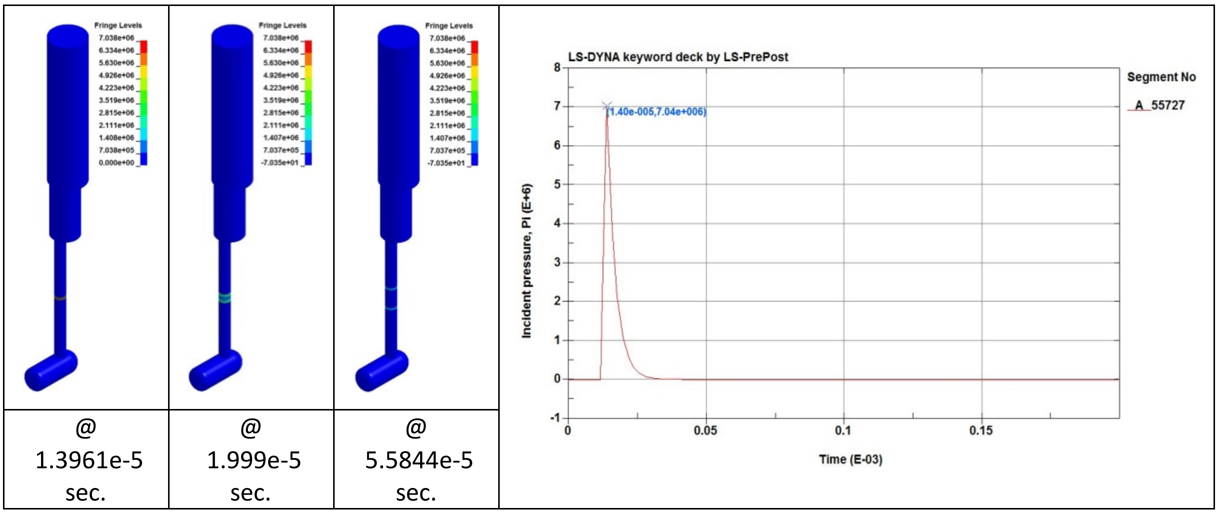


Figure 8 Incident pressure wave contour and history plot (helium transfer pipe)

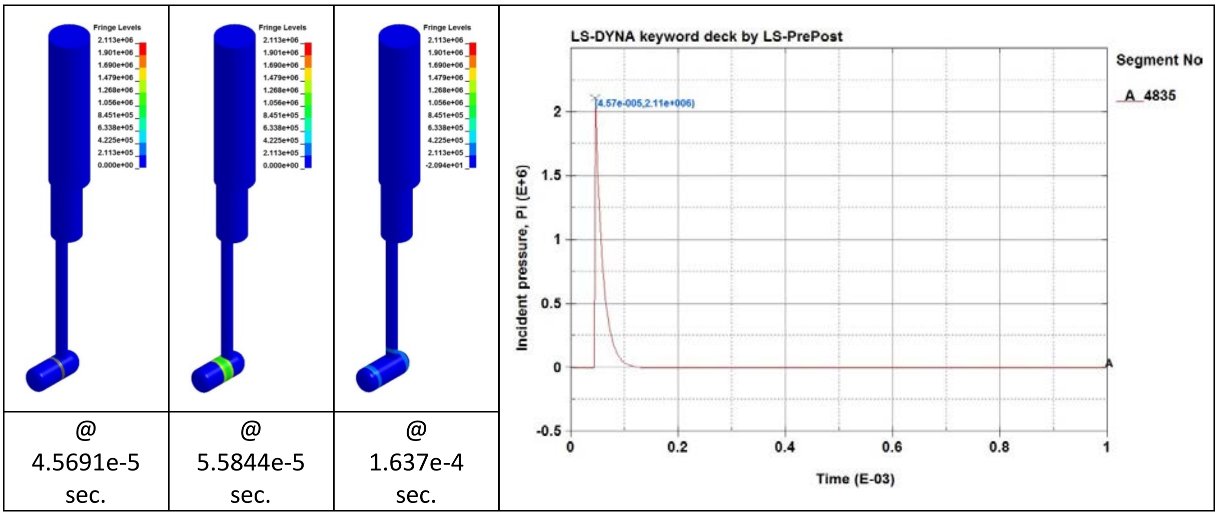


Figure 9 Incident pressure contour and history plot (helium containment vessel)

Table 2 Assessment results and safety margins

Simulation case	Blast position	Incident pressure (P_{max} (bar))	Duration time (θ (sec.))	P_{equ} (bar)	Pressure by design rules [2]	Safety margin
No. 1	Helium housing (upper)	7.01	2.6e-5	10.447	38.1	3.6
No. 2	Helium housing (lower)	12.90	1.8e-5	17.916	35.1	1.9
No. 3	Helium transfer pipe	70.38	1.9e-6	31.439	65.3	2.0
No. 4	Helium containment vessel	21.13	1.01e-5	21.484	33.2	1.5

The computed equivalent static pressure (P_{equ}) for the hypothetical hydrogen explosion is much less than the maximum pressure calculated by the design rules about the current IPA design. The safety margin is over 1.5 at least, as shown in Table 2.

Each components of the IPA shall be constructed in accordance with the requirements of the relevant Codes and Standards. The ASME Codes and Standards provide us the design rules for the construction of a vessel, tank, pipe, and flange. All components are designed by rules of the Codes and Standards to have sufficient safety margins under various loading conditions such as the design condition, normal conditions including the start-up and shutdown, abnormal conditions, emergency conditions, faulted conditions, and test conditions. In addition to these design by rules, a numerical analysis utilizing the commercial finite element software was also performed to verify the structural integrity of the IPA.

For example, Figure 10 illustrates the finite element model for the moderator cell of the IPA. The moderator cell shall satisfy the requirements for the protection from failure modes according to ASME Section VIII (Division 2). For the assessment, the equivalent stress values are evaluated by the commercial finite element software, ANSYS workbench ver. 16.0. Numerical simulations were carried out for four kinds of failure modes, such as a plastic collapse, local failure, collapse from buckling, and failure from cyclic loading. The simulation results showed that the moderator cell has a sufficient safety margin compared to the acceptance criteria requested by the relevant Codes and Standards.

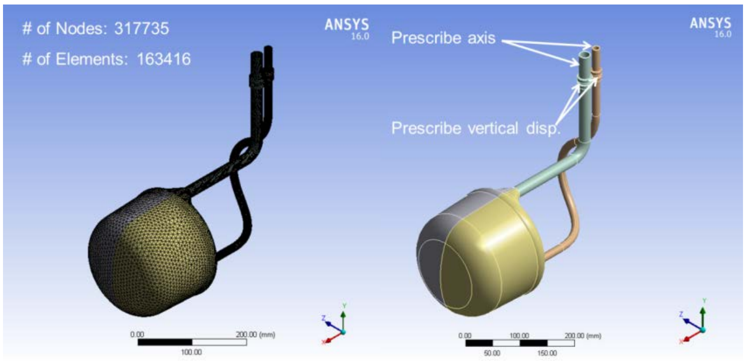
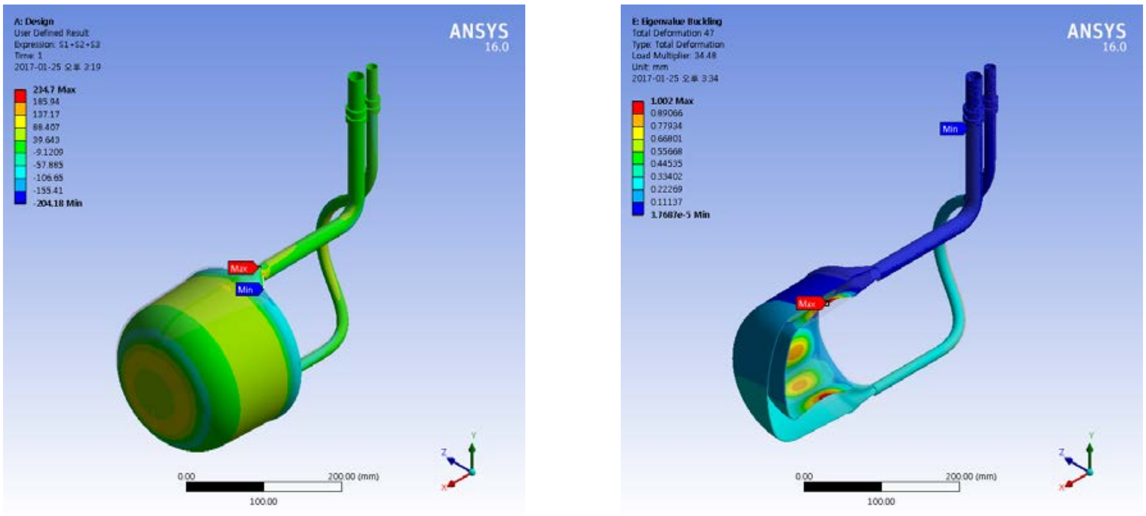


Figure 10 Finite element model for moderator cell



(a) (b)

Figure 11 The sum of principal stress and buckling mode of the moderator cell

3 Conclusions

The IPA was designed to have sufficient safety margins in accordance with the relevant Codes and Standards even under the worst-case accident of a hypothetical hydrogen explosion, and verified with various numerical analyses. For the moderator cell and the second containment components such as a vacuum chamber, vacuum transfer pipe, and vacuum housing, the essential design parameters were determined through the "Design by Rules," which is based on the ASME Section VIII Division 1, and verified numerically by the "Design by Analysis" which is based on the requirements of the ASME Section VIII Division 2 [4]. The pipes were designed according to the ASME B31.3. The design parameters of the components for the third containment such as the helium containment vessel, helium transfer pipe, and helium housing were determined in compliance with the ASME Section III ND, and verified numerically [5].

4 References

[1] ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, Rules for Construction of Pressure Vessels. 2013 Edition, American Society of Mechanical Engineers.

[2] ASME Boiler and Pressure Vessel Code, Section III, Division 1 – Subsection ND, "Class 3 Components", Rules for Construction of Nuclear Facility Components, 2013 Edition, American Society of Mechanical Engineers.

[3] ASME B31.3-2012 Edition, "Process Piping", American Society of Mechanical Engineers.

[4] ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Alternative Rules for Construction of Pressure Vessels. 2013 Edition, American Society of Mechanical Engineers

[5] ASME Boiler and Pressure Vessel Code, Section III, Division 1 – Subsection NB, "Class 1 Components", Rules for Construction of Nuclear Facility Components, 2013 Edition, American Society of Mechanical Engineers