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Safety design consideration for HTGR coupling with hydrogen production plant

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ABSTRACT

Safety requirements and design considerations are examined for a nuclear hydrogen production system that consists of High Temperature Gas-cooled Reactor (HTGR) and a hydrogen production plant by thermochemical water splitting iodine–sulfur process (IS process). Requirements in order to construct hydrogen production plants under conventional chemical plant regulation are identified in order to take into account a fundamental difference in safety philosophy between the nuclear facility and chemical plant and meet requests from the potential users of nuclear heat. In addition, safety requirements for the collocation of the nuclear facility and hydrogen production plant utilizing IS process (IS plant) are investigated. Furthermore, design considerations to comply with the requirements are suggested and the technical feasibility of the design considerations is evaluated. The evaluation results for a reference plant showed that safe distance determined by the chemical plant regulation against combustible gas and hazardous chemical leakages comply with the plant layout design. Furthermore, the results demonstrated the feasibility of IS plant construction under non-nuclear regulation by showing that the tritium concentration in IS plant can be maintained below the regulation limit and reactor normal operation can be achieved during abnormal conditions in the IS plant. These results clarified that design considerations suggested for coupling the IS plant to HTGR are reasonably practicable. The proposed criteria can be used not only for coupling hydrogen production plants but also for other chemical plants such as steam reforming plants, etc.

1. Introduction

Hydrogen demand is expected to rise significantly in the near future for various areas of application such as fueling automobiles, reducing iron ore, producing ammonia, etc. However, current production processes of hydrogen highly depends on steam methane reforming of natural gas, which results in emission of large quantities of carbon dioxide. Thermochemical processes using nuclear energy as the primary energy source is one of the promising candidates to replace existing hydrogen processes because hydrogen can be massively produced without relying on fossil fuels.

Towards the realization of nuclear hydrogen production, safety requirements for integrated nuclear hydrogen production system must be established. In addition, it is required to have design considerations not only to meet the requirements but also to be practically acceptable. For an example, locating the hydrogen production plant away from the nuclear reactor results in undue cost increase because of the increase in piping length of heat transfer loop as well as decrease in hydrogen production rate by efficiency reduction. Several studies have been made on safety of nuclear hydrogen production system. US NRC performed the identification of phenomena relevant to the safety of nuclear facility when coupling hydrogen production plant (US NRC, 2008). Ohashi et al. investigated the abnormal events in hydrogen production plant which would affect evaluation items in reactor safety analysis by Master Logic Diagram and proposed a basic safety philosophy of nuclear facility against identified events (Ohashi et al., 2007). Murakami et al. examined evaluation methods for abnormal events of safety significance to nuclear reactors which may occur in the hydrogen production plant (Murakami et al., 2006, 2008). Sakaba et al. proposed a basic idea to construct hydrogen production plants not under nuclear power plant regulation but under industrial legislation, e.g. High Pressure Gas Safety Act, in order to accommodate requests from chemical industries.

In the present study, we investigate requirements to ensure the safety of the nuclear facility against abnormal events initiated in

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the hydrogen production plant as well as to construct hydrogen production plants not under jurisdiction of nuclear regulatory authority on the basis of above studies and the safety design of the High Temperature engineering Test Reactor (HTTR), which was authorized by Japanese regulatory authority, in order to avoid omission in identification of safety-relevant issues related to the coupling of hydrogen production plant. We also examined tangible design considerations to meet the identified requirements. In addition, the technical feasibility of design considerations for a representative system is evaluated.

2. Safety design philosophy of HTGR hydrogen production system

2.1. Overview of HTGR hydrogen production system

Present study focused on a nuclear hydrogen production system that consists of High Temperature Gas-cooled Reactor (HTGR) and a hydrogen production plant by thermochemical water splitting iodine–sulfur process (IS plant). A schematic of a representative configuration for the system is shown in Fig. 1.

HTGR is a helium-cooled, graphite-moderated, thermal-neutron-spectrum reactor with core outlet temperature up to 950 °C in nominal operation. High temperature heat supply capability and inherently safe characteristics of HTGR with reliance on such material uses as inert, single-phase helium coolant, refractory coated fuel particle, and heat-resistant graphite moderator allow collocation with industrial facilities.

The IS process is a method of hydrogen production by splitting water thermo-chemically without carbon dioxide emission using the following three chemical reactions.

$$SO_2(g) + I_2(l) + 2H_2O(l) \rightarrow 2HI(aq) + H_2SO_4(aq) \quad (1)$$

$$H_2SO_4(aq) \rightarrow H_2O(g) + SO_2(g) + 0.5O_2(g) \quad (2)$$

$$2HI(g) \rightarrow H_2(g) + I_2(g) \quad (3)$$

The heat required for the endothermic reactions and concentration of acids is supplied to process heat exchangers (PHXs) by helium gas from HTGR through an intermediate heat exchanger (IHX).

2.2. Basic philosophy of safety design

Basic requirements for coupling IS plant to nuclear facility are:

(a) Assurance of safety for nuclear facility against postulated events initiated in IS plant, and
(b) Certification of IS plant as a non-nuclear facility, that is, construction of IS plant under non-nuclear regulation.

First requirement originates in fundamental safety objective of nuclear facility which should not be altered even in the case of HTGR hydrogen production system. The reason of second requirement is mainly due to the fundamental difference in safety philosophy between the nuclear facility and chemical plant. The objective of safety design in nuclear facility is to confine radioactive materials within the facility. On the other hand, confinement of materials contained in chemical plant may increase an individual risk to the public and workers because of confined explosion and hazardous chemical accumulation. The other reason is to comply with requests from potential users of nuclear heat from the economical point of view. In general, components manufactured for a nuclear facility are two-to-three times more expensive than those prepared for non-nuclear facility (The Economic Modeling Working Group of the Generation IV International Forum, 2006). It is expected that the construction of IS plants under industrial regulation would significantly reduce investment cost, which is dominated by equipment cost (Sakaba et al., 2008).

2.3. Postulated safety-related phenomena in IS plant

The following phenomena postulated in the IS plant were identified from a safety viewpoint (Ohashi et al., 2007).

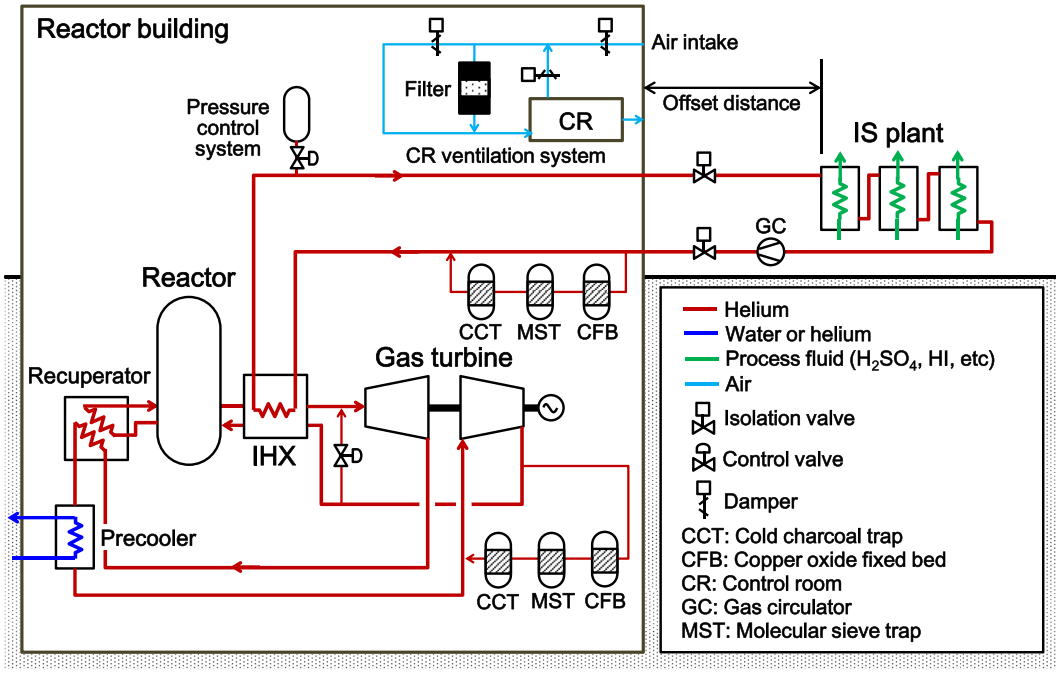

Fig. 1. Schematic diagram of a representative HTGR hydrogen production system and design considerations.