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Safety concept of nuclear cogeneration of hydrogen and electricity

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ABSTRACT

There is a significant potential for nuclear combined heat and power (CHP) in quite a number of industries. The reactor concepts of the next generation would be capable to open up, in particular, the high temperature heat market where nuclear energy is applicable to the production processes of hydrogen (or liquid fuels) by steam reforming or water splitting. Due to the need to locate a nuclear facility near the hydrogen plant, an overall safety concept has to deal with the question of safety of the combined nuclear/industrial system by taking into account a qualitatively new class of events characterized by interacting influences. Specific requirements will be determined by such factors as the reactor type, the nature of the industrial process, the separation distances of the industrial facility and population centers from the nuclear plant, and prevailing public attitudes. Based on the Japanese concept of the GTHTR300C nuclear reactor for electricity and hydrogen cogeneration, theoretical studies were conducted on the release, dispersive transport, and explosion of a hydrogen cloud in the atmosphere for the sake of assessing the required minimum separation distance to avoid any risk to the nuclear plant's safety systems. In the case of sulfur-iodine water splitting, the accidental release of process intermediates including large amounts of sulfur dioxide, sulfur trioxide, and sulfuric acid need to be investigated as well to estimate the potential risk to nuclear installations like the operators' room and estimate appropriate separation distances against toxic gas propagation. Results of respective simulation studies will be presented.

Introduction

A strong increase in the demand for hydrogen is foreseen in near future. Not only are rapidly growing markets for hydrogen anticipated in the chemical industries, a.o. as a raw material for upgrading of mined oil resources, but also as clean fuel in the transportation sector. An essential question will therefore be of how to generate and supply hydrogen in sufficient quantities. More than 95% of the world's hydrogen production are generated on the basis of fossil fuels. Given their serious impact on the climate, they have to be gradually substituted by clean alternatives. Water is expected to become a major source for hydrogen in the future with the necessary

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process heat for extracting the hydrogen to be provided by CO_2 emission free energy sources. With respect to hydrogen production on a large scale at a constant rate, nuclear energy may play an important role.

Modern nuclear power plants (NPP) are generally considered to represent a safe, reliable, clean, and economic energy source with still a huge potential for nuclear combined heat and power (CHP) in quite a number of industries. The reactor concepts of the next generation would be capable to open up, in particular, the high temperature heat market where nuclear energy is applicable to the production processes of hydrogen (or liquid fuels), thus contributing to the development of domestic energy sources for the purpose of energy security and stability, and reduction of national dependencies on fossil fuels imports. The high temperature gas-cooled reactor (HTGR) is a helium-cooled, graphite-moderated, thermal-neutron-spectrum reactor. If operated at coolant outlet temperatures of 950 °C, it represents a promising system to allow the cogeneration of heat and steam at high temperatures as well as electricity in an efficient manner. Characteristic safety features such as inert, single-phase helium coolant, refractory coated particle fuel, and heat-resistant graphitic materials will facilitate a collocation with industrial facilities.

The Japan Atomic Energy Agency (JAEA) has developed the concept of a nuclear hydrogen production system [1] with an HTGR connected to a hydrogen production plant based on the sulfur-iodine (S-I) thermochemical water splitting cycle, a process which has also been intensively studied within the European Commission funded project HYTHEC [2]. The heat required for the endothermic reactions in the different process steps is supplied by helium gas from HTGR via an intermediate heat exchanger (IHX) to the secondary helium circuit and from there via process heat exchangers to the hydrogen production plant. Due to the need to locate a nuclear facility near the hydrogen plant, a decent overall safety concept has to deal with the question of safety of the combined nuclear/industrial system by taking into account interacting influences. Specific requirements will be determined by factors such as reactor type, nature of the industrial process, separation distances of the industrial facility and population centers from the nuclear plant, and prevailing public attitudes.

Safety philosophy of nuclear hydrogen production

There is a fundamental difference in the safety philosophy between a nuclear and a chemical plant. The objective of safety design in nuclear facility is to confine radioactive materials within the facility. In contrast, confinement of materials contained in chemical plant may increase an individual risk to the public and workers because of potential confined explosions and hazardous chemical accumulation. In a water-splitting hydrogen production system, H_2 and O_2 are produced simultaneously so that there is a possibility of an internal explosion if inadvertently mixed. On the other hand, the two gases are produced in different process steps which are physically separated. To prevent internal explosions, an emergency purge system shall be provided to remove hydrogen from pipes and vessels.

Fire and explosion of hydrogen is the most significant consequence of hydrogen release. If ignited during leakage, jet flames are formed that may damage components by overheating. According to the safety design regulations for chemical plants, leak detectors and emergency shutoff valves shall be provided for detecting and stopping a leakage of hydrogen as soon as possible. Components shall be arranged with an appropriate separation distance to eliminate secondary failure. The length of the jet flame may be several meters and the safety items in the HTGR are placed a hundred meters away from the hydrogen production system, so a jet flame would not directly damage any nuclear safety-related systems.

If hydrogen does not ignite during leakage, a combustible hydrogen-air cloud evolves which may result in a delayed flash fire that could cause damage by emission of strong heat. The flash fire is a deflagration without overpressure and would, therefore, not impair the safe conditions of the control room and rather allow continuing the safe operation of the HTGR. In case of a hydrogen-air gas cloud explosion, the resulting overpressure may damage the reactor building or components installed outside the HTGR. Densely arranged obstacles shall not be placed between the HTGR and the hydrogen production system, since they may accelerate the burning velocity and generate a stronger overpressure. Vessels and pipes in the hydrogen production system shall be arranged with suitable space to not support flame acceleration.

The essential requirements for coupling a nuclear with a hydrogen production plant are [3].

(a) the assurance of the safety of the NPP against postulated events initiated in the hydrogen plant in order to guarantee cooling of secondary helium circuit during normal operation and maintaining the differential pressure between primary and secondary helium circuit, and
(b) the construction and operation of the hydrogen plant as a conventional, non-nuclear facility by mitigating tritium concentrations in the hydrogen plant below the limits allowed by legislation (country-dependent) in order to guarantee a radioactivity-free hydrogen plant.

The reinforced concrete wall of the HTGR reactor building and components placed outside must be designed to withstand severe external loads including not only the above mentioned gas cloud explosions but also the wind forces of a typhoon or the ground motion of an earthquake [4]. In German and Russian design codes of the nuclear power plant for the explosion accident, the design limit of overpressure on safety plant structures is 30 kPa. If there is a risk of exceeding this limit, a detailed analysis shall be performed to verify the structural integrity of reactor building and components. A release of chemical compounds such as SO_2, SO_3, H_2SO_4, HI, and I_2, which are interim products in the S-I cycle, into the atmosphere may cause spreading of these toxic materials eventually penetrating the NPP control room through ventilation systems. The safety design requires

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