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.

1.0 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 for clean alternatives. Water is expected to become a major source for hydrogen in the future with the necessary 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 characteristics 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.

2.0 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 vapor 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 of the hydrogen-air cloud and generate a stronger overpressure. Vessels and pipes in the hydrogen production system shall be arranged with suitable space to eliminate 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 vapor cloud explosions but also the wind forces of a typhoon or the ground motion of an earthquake. 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 ensuring the capability of the functions of structures, systems and components, prevention and mitigation of accident consequences, and maintaining habitability of the control room.

3.0 DESCRIPTION OF THE GTHTR300-IS SYSTEM

1.1 Design of Nuclear Heat Source

Based on the experience with the construction and operation of the 30 MW(th) HTTR test reactor with an average coolant exit temperature of 950°C [4, 5], JAEA has further developed the nuclear reactor technology and elaborated a commercial-scale concept of an HTGR to be used for hydrogen and electricity cogeneration (Fig. 1) [6].

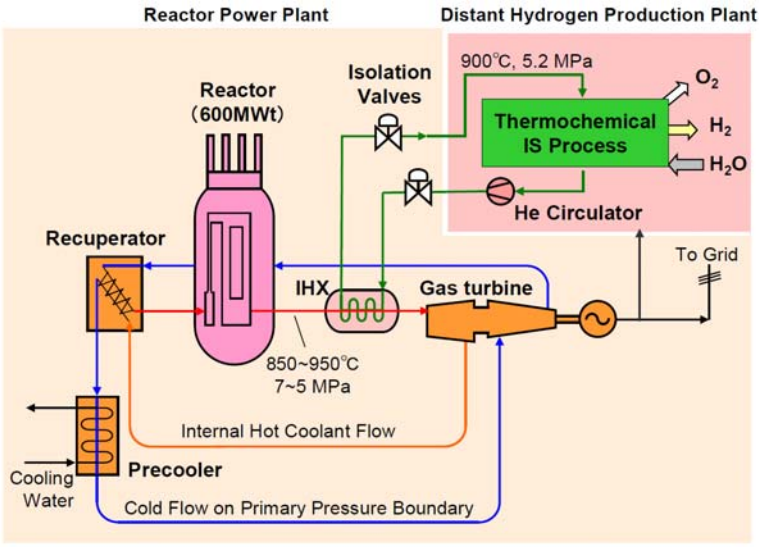

Figure 1. GTHTR300C S-I thermochemical hydrogen cogeneration process

The direct cycle gas turbine generates electricity and circulates the reactor coolant helium. Hydrogen cogeneration is enabled by adding the IHX in serial between the reactor and the gas turbine. This arrangement offers the important design benefit that there is only one main coolant loop self-circulated by the gas turbine, eliminating the need of a separate circulator and motor drive. Also, the cogeneration ratio of hydrogen and power is made variable and the power can be generated at constant aerodynamic operation of gas turbine up to full thermal power of the reactor [7]. A bypass control valve is used to maintain turbine inlet temperature constant by directing colder coolant from the reactor inlet location to mix with the hotter gas exiting the IHX so that the turbine inlet temperature is maintained at constant 850°C. The maximum power that can be sent out to external grid is 276 MW(e), raised from the cogeneration level of 178 MW(e) within as little as seven minutes. The reactor coolant pressure increases from 5 to 7 MPa. To return to the rated cogeneration mode, the above process is reversed by reducing coolant inventory in the primary coolant circuit and closing the bypass control valve while increasing the heat load in the process heat exchanger. A secondary helium loop circulates hot helium from the IHX to the hydrogen plant over a sufficient separation distance. The secondary loop including safety design measures such as isolation valves provides for physical and material separation between the nuclear plant and the conventional-grade hydrogen plant.

The box of "distant hydrogen production plant" in the above figure represents the sulfur-iodine thermochemical process for hydrogen production. The process includes three inter-cyclic thermo-chemical reactions to dissociate water molecules into hydrogen and oxygen gas products with major heat and minor electricity as energy input and with water as the only material feed. All process materials other than water are reagents and are – ideally – recycled. The heat and electricity requirements are met in-house by the reactor plant.

The secondary loop has interfaces with two key chemical reactor sections. The first is a compact sulfuric acid decomposer which requires the highest temperature at a level of about ~900°C. The hot helium enters to flow up in the inner of the concentric tube while heating and decomposing the downward flow of SO_3 in the annulus of the tube. The helium at a reduced temperature turns to flow down in the tubes of the upper heat exchanger, wherein the SO_3 is preheated, and leaves the heat exchanger at mid-level. The H_2SO_4 liquid enters the shell side of the lower heat exchanger and is

decomposed with the heating of hot SO_2 in the tube side. The other chemical reactor, to which the secondary loop interfaces, is the HI decomposer. This unit consists of internally sequential stages of the HI decomposing reaction. The hot helium of the secondary loop flows upward in the shell of the reactor steel vessel while heating a series of chemical process stages. The flow scheme is configured to facilitate the inter-stage removal of the reaction product iodine by scrubbing of the iodine-lean aqueous HIx solution stream that counter-flows to the overall HI decomposition solution stream.

Figure 2 details the heat and mass balance of the hydrogen production section. The thermal rate transported by the secondary loop hot helium from the nuclear reactor to the hydrogen plant is used to heat process heat exchangers and decomposers. The electricity power totaling 21.7 MW(e) is used to power the process HI purification electrolyzers (13 MW(e)), the secondary helium circulator, the hydrogen process gas circulators and pumps, and other utilities. The process yields a production rate of 26,829 Nm^3/h or ~2.4 t/h of hydrogen, and of 13,515 Nm^3/h or ~9.7 t/h of the by-product oxygen.

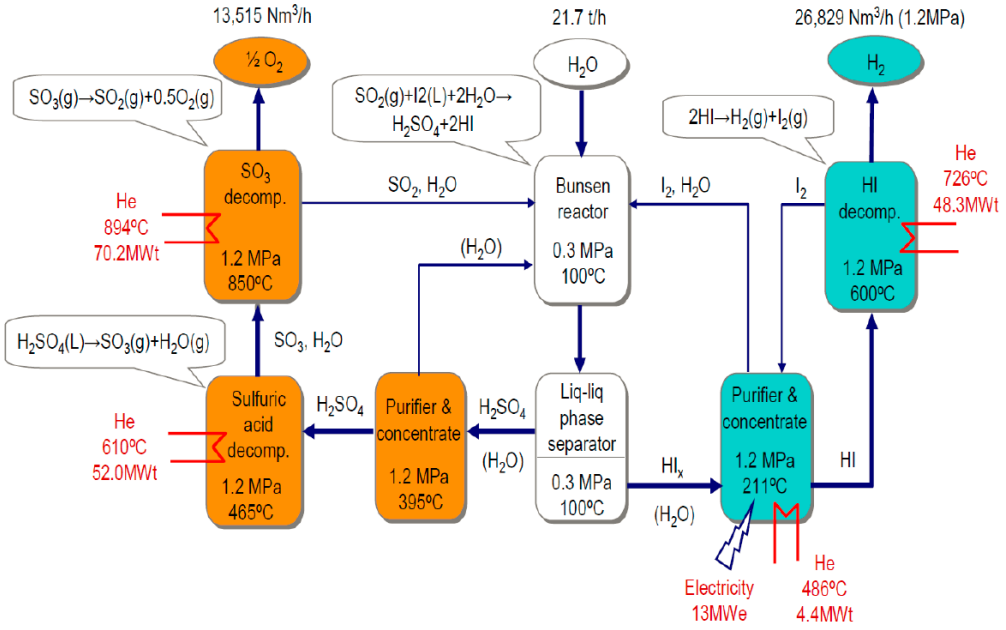

Figure 2. Heat and mass balance of the 170 MW(th) rated S-I process

Table 1 provides key performance parameters of the GTHTR300C in both power generation and hydrogen cogeneration modes. In the baseline condition of the cogeneration mode, 170 MW(th) of the reactor thermal power is extracted via the IHX as 900°C process heat supply to the hydrogen production process and the balance of reactor thermal rate is used for electricity generation. A fraction of the 200 MW(e) electricity generated supplies plant in-house operations, mainly the hydrogen plant operations to power electrolyzers, circulators, pumps and other utilities, while exporting a more significant fraction to the grid.

4.0 EVALUATION OF A SEPARATION DISTANCE BETWEEN NUCLEAR AND CHEMICAL PLANT

There are two significant safety issues originated in the thermochemical hydrogen production system to be coupled to the HTGR, the release of hydrogen and the release of toxic gas. Basic safety design approach is to prevent accidental release of these materials and to mitigate their effect on the HTGR safety items and operators. Provision of separation distance between the HTGR and the hydrogen production system is a simple and reliable safety approach.

Table 1. Performance parameters of the GTHTR300C plant.

Reactor thermal power per module [MW(th)]	600
Core power density [MW/m^3]	5.4
Reactor lifetime [yr]	60
Plant availability [%]	90+
Reactor fuel cycle	LEU, MOX, others
Helium flow rate [kg/s]	324
Helium inlet temperature [°C]	594
Helium outlet temperature [°C]	950
Helium pressure [MPa]	5.1
GT conversion cycle	Non-intercooled direct Brayton cycle
Power generation efficiency [%]	47
Net electricity output [MW(e)]	174
H_2 plant effective heat rate (MW(th))	220
H_2 conversion process	Thermochemical (or hybrid) cycle
H_2 conversion efficiency [%]	43
H_2 production [m^3/d]	6.5×10^5
Total plant efficiency net [%]	45

4.1 Separation Distance with regard to Hydrogen Explosion

A hydrogen gas cloud can move over a longer distance depending on the release conditions and the atmospheric conditions. The separation distance between the hydrogen production system and the HTGR plant should be determined to prevent ingress of a flammable hydrogen cloud into the reactor building through the ventilation system of the HTGR. JAEA performed an analysis of the separation distance adopting the computational fluid dynamics code STAR-CD to evaluate in a three-dimensional rectangular coordinate system the hydrogen concentration in the field. The computational domain and the layout of release point and protective wall are shown in Fig. 3. The release point is set at x = 30 m, y = 0 m. The vertical position of the z direction is an input parameter. The symmetry model of x–z plane is employed to reduce the mesh number.

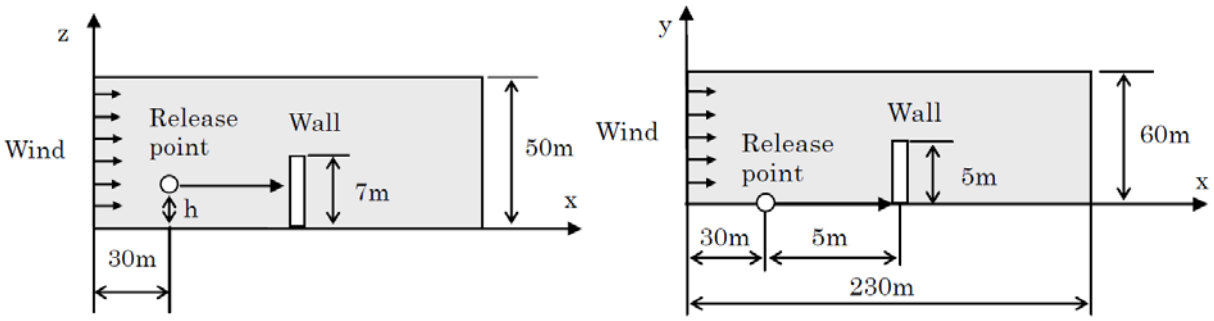

Figure 3. Layout of computational domain with release point and protection wall

Pressurized hydrogen gas blows out from a failed pipe like a jet at critical speed. The mass flow rate is decreasing with decreasing pressure in the H_2 tank according to the following equation:

$$m_c = A \frac{p_0}{\sqrt{R\,T_0}} \sqrt{\kappa \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa+1}{\kappa-1}}} \,, \qquad (1)$$

where p_0 and T_0 – pressure, Pa, and temperature, K, of hydrogen in pipe; A – cross section area of pipe, m^2; R – gas constant of hydrogen, = 4124.6 J/(kg·K); κ – ratio of specific heats, = 1.403.

For conservative reasons, a constant pressure is assumed during leakage at the initial condition. Duration of the gas release is given by dividing the amount of hydrogen released by the mass flow rate. Compressibility of the H_2 gas affects its concentration only close to the opening of the pipe. Since this analysis focuses on analyzing the dispersion behavior in the open field, the compressibility effect can be neglected here. The atmospheric condition is an important factor of the diffusion analysis. The standard k–ε model is adopted in the turbulent flow model of this analysis. A steady-state analysis for each wind speed is conducted to determine the initial atmospheric condition. Analytical parameters which are the amount of hydrogen released, the pipe diameter, height of the release point, the wind speed, and the horizontal angle of jet, are listed in Table 2. The calculation results of H_2 gas concentrations based on the table data (reference case) are shown in Fig. 4 indicating the downwind movement of the vapor cloud and also its dispersion both in horizontal and in vertical direction. The flammable portions of the cloud marked in red are expected to become smaller with time.

Table 2. Analytical conditions for hydrogen release.

		Reference case
Amount of hydrogen released [kg]	~10, 25, 58, 97	97
Pressure [MPa]	4	4
Pipe diameter [mm]	20, 100	100
Height of release point [m]	0, 2.5, 5	2.5
Wind speed [m/s]	1 – 15	1
Horizontal angle of jet	0° – 90°	0°
Atmospheric stability category	stable	stable

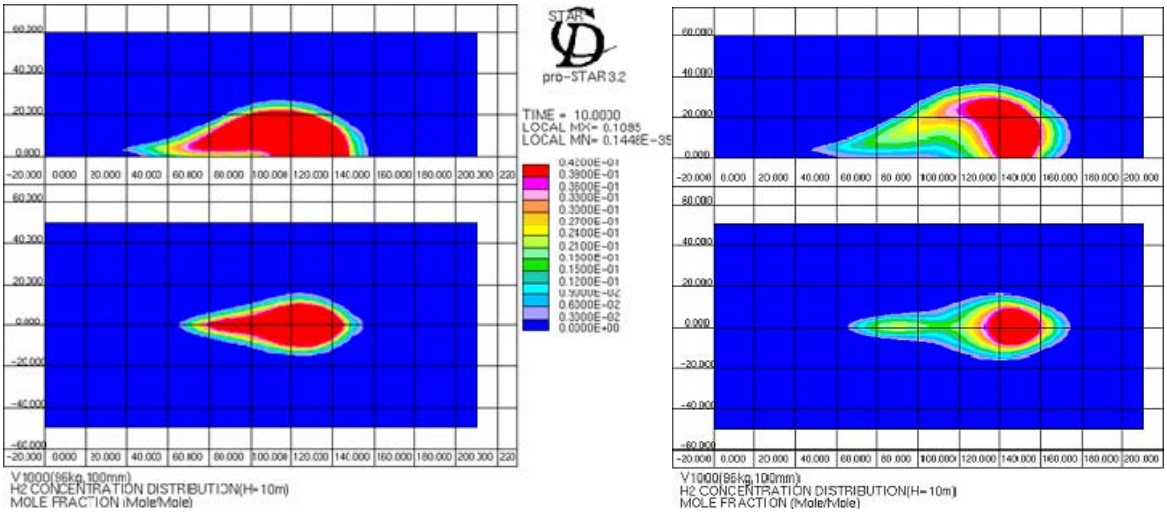

Figure 4. Hydrogen gas concentration distribution after 10 s (left) and after15 s (right), x–z cross section in upper part, x–y cross section at height z=2.5 in lower part, red color indicating the area of H_2 concentrations within the flammability limits

Sensitivity calculations have been performed to assess the influence of various parameters on the transient hydrogen-air cloud behavior.

The relationship between moving distance of the flammable hydrogen cloud (defined as the projected distance on the ground from the release point to the edge of the flammable hydrogen cloud) and hydrogen mass of the flammable cloud is shown in Fig. 5a for the 97 kg release case. The moving distance (black symbols) is steadily increasing throughout the time frame considered. During the release phase of 5 s, the H_2 mass of the flammable cloud (white symbols) is increasing. Upon cessation of the gas release, the H_2 mass gradually decreases by dispersion. The flammable H_2 mass reaches a maximum of about 45 kg meaning that more than half of the released hydrogen remains at a concentration level < 4%.

Figure 5b, shows the effect of the released amount of hydrogen on the moving distance. Increasing the amount of released hydrogen leads to larger moving distances and to an extension of the release duration. The release of a small amount of hydrogen gas (here ~10 kg) can be considered instantaneously (release time: 0.5 s), while a larger amount of hydrogen gas is released semi-continuously (e.g. 97 kg within 5 s). The maximum moving distance, however, does not increase linearly with the hydrogen mass released; the difference in the distances estimated for 58 and 97 kg is only 9 m.

The pipe diameter has a direct effect on the release rate and the duration as is indicated in Fig. 5c. Release mode for small pipe diameters is a continuous release and its moving distance is shortest. The figure demonstrates that a larger-size pipe rupture is more significant for the moving distance.

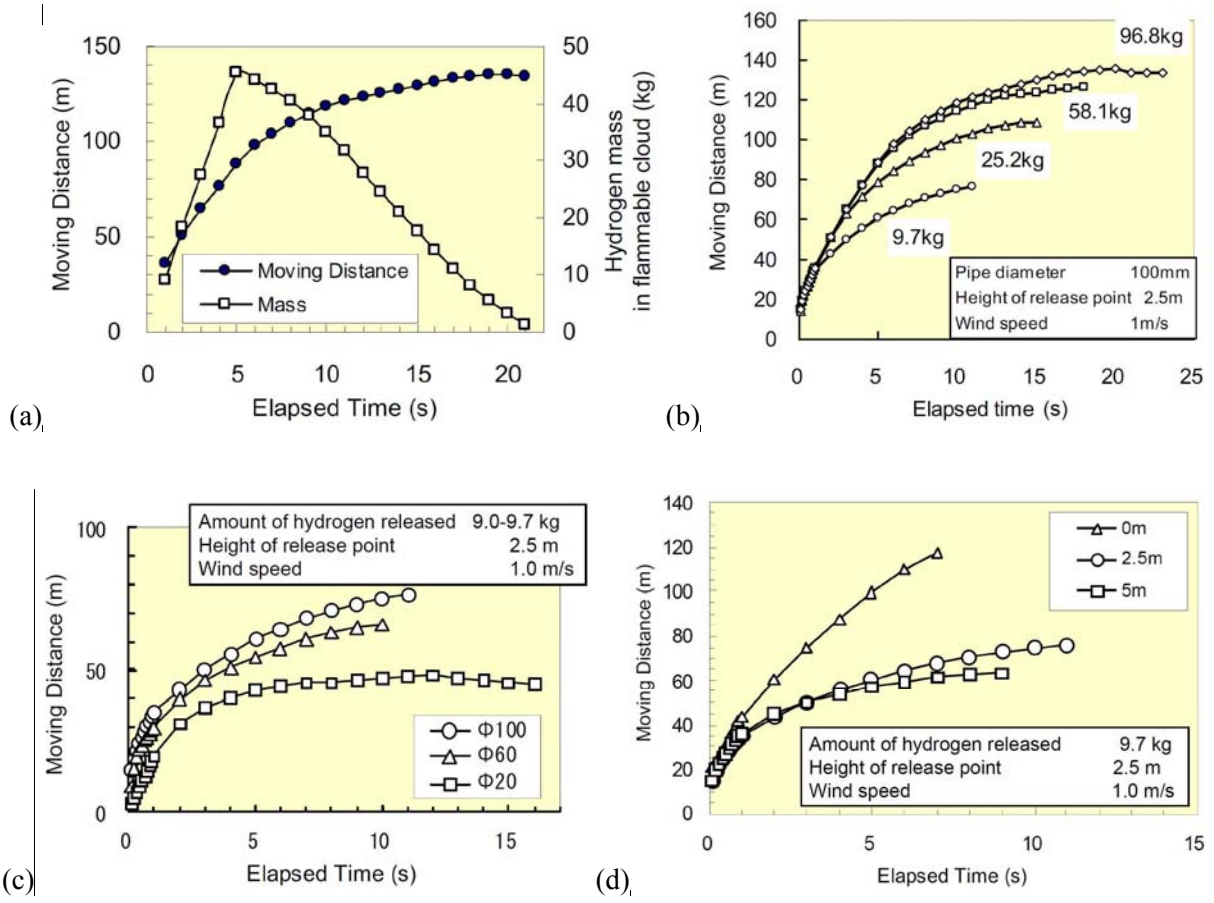

Figure 5. Relationship between moving distance and H_2 mass of the flammable cloud (a) and effects on the moving distance by variation of amount of H_2 released (b); pipe diameter (c); release height (d)

Hydrogen transport pipes are generally installed overhead to prevent gas retention and accumulation under vessels and structures and to take benefit of enhanced dispersion of the H_2 gas because of its light nature. Figure 5d shows the effect of the height of release point on the moving distance. The ground release leads to the longest moving distance because dispersion in z direction initially is small due to slower mixing with air. The results for the heights of 2.5 m and 5 m are almost the same. Conclusion from this result is that an installation of the hydrogen pipe on the ground should be excluded.

A physical barrier is an effective means to reduce the moving distance of the hydrogen cloud. In another calculation, the effect of the wall installed near the hydrogen transportation pipe has been analyzed. The thickness of the wall should be fixed as to withstand the load of blast overpressure generated by the hydrogen explosion. For example, the minimum thickness of the blast-proof wall

made of reinforced concrete is 120 mm in Japanese industrial codes. Further assumptions for the wall were a length of 15 m, the height to be 2 m higher than the release point and a distance 5 m away from the release point (see Fig. 3). Primary effect discovered was a drastic decrease of the moving distance of the flammable cloud portion. For a horizontal release, two cloud cells of enhanced concentrations were forming behind either side of the wall, while a low-concentration cell was formed from the gas passing above the wall. Assuming, however, a release angle of 22.5°, a larger cloud cell forms above the wall plus two smaller cells are formed on the sides, all without any flammable portion. The effect of the wall disappears completely at release angles over 45°.

The upper limit of the peak overpressure of structures is an important item to determine the safe distance in the safety design. While, for example, Russian regulation prescribes a design value of 30 kPa for an NPP building to withstand a shock wave, the Japanese industrial code recommends 10 kPa from the viewpoint of no significant damage to the public. For this analysis, the design limit was tentatively set at 10 kPa to evaluate a conservative separation distance.

There are various calculation methods applicable to estimate the effect of blast overpressure generated by a hydrogen explosion. The two essential parameters of concern regarding the impact on structures and equipment are peak overpressure and impulse. The peak overpressure is employed as indicator in many codes and guidelines because of its simplicity. Intensity of the overpressure can be assessed, e.g., by the multi-energy method [8]. A corresponding blast chart was created based on an idealized gas explosion analysis where a combustion energy of 3.5 MJ/m^3, stoichiometric concentration of charge–air mixture, and a semi-spherical shape of the cloud were assumed. There are ten classes in the chart identified by the initial blast intensity. Class 10 represents a detonation; class 7 represents a strong deflagration, while class 5 represents a hydrogen explosion with low ignition energy and several obstacles. An explosion in the hydrogen production system may correspond to a level between class 5 and class 7.

The separation distance is defined by the sum of moving distance of the flammable hydrogen gas cloud and distance of the peak overpressure of 10 kPa derived from the explosion of this gas cloud. Figure 6 shows the calculated separation distances for the reference case (see Table 2). When 97 kg of hydrogen is exploded at the release point, which is a conventional evaluation method, the required separation distance is 62.5 m. However, as can be seen from the figure, the overall separation distance is greatly increased when taking account of the moving distance.

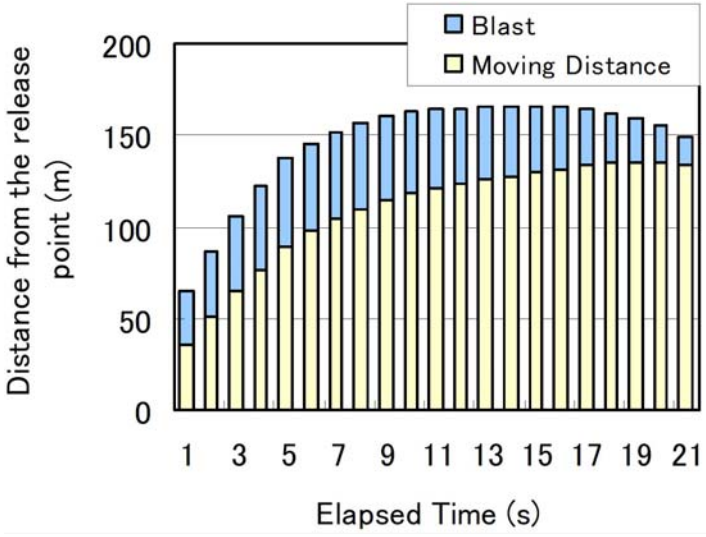

Figure 6. Distance from the release point suffering an overpressure of 10 kPa

4.2 Separation Distance with regard to Toxic Gas Release

In order to operate safely in all operational states, the control room of the HTGR plant shall be protected against the potential release of toxic materials such as sulfur dioxide, sulfur trioxide, sulfuric acid and hydrogen iodine that are present in the S-I cycle-based hydrogen production system. To maintain the control room in a safe state or to bring it back into a safe state, appropriate measures shall

be provided to decrease the toxic gas concentrations in the control room to below the acceptable limits. When a gas concentration exceeds a given limit, the ventilation system shall be shutdown to isolate the control room from the outside air and the recirculation air filter system in the control room will operate to reduce the toxic gas concentration to below the acceptable limit.

Upper limits of toxic gas concentrations for human beings are defined in many guidelines. The US-NRC regulatory guide, for example, recommends upper limits of "immediately dangerous to life and health" (IDLH) values [9]. The IDLH limits are the values for 30 minutes exposure limit to eliminate death or permanent adverse health effects. Physical incapacitation does not occur within two minutes of exposure. According to the safety approach considered by JAEA, the upper limits of toxic gas concentrations in the control room have been decided sufficiently low such that a 60-minutes exposure can be permitted. Furthermore, the "emergency response and planning guideline" (ERPG) by the American industry health association (AIHA) and "acute exposure guideline level" (AEGL) by the US-EPA are adopted [10].

In the EPRG guideline, three levels of gas concentration limits for sulfuric acid, sulfur dioxide and sulfur trioxide for one hour exposure are defined as shown in Table 3. ERPG-1 is the limit without experiencing mild and transient adverse health effects. ERPG-2 is the limit without experiencing serious health effects or symptoms which could impair the ability to take protective action. ERPG-3 is the limit without experiencing life-threatening health effects. AEGL defines five levels for exposure period from 10 minutes to 8 hours. AEGL-1 is for 8 hours exposure limit and AEGL-2 is for 1 hour exposure limit. The comparison of these exposure limits is also shown in the table.

Table 3. Upper limits of toxic gas concentrations [mg/m^3].

Chemical	IDHL	JAEA toxicity limits	EPRG-1 (1 h)	EPRG-2 (1 h)	EPRG-3 (1 h)	AEGL-2 (1 h)	AEGL-1 (8 h)
SO_2	262	520	0.9	8.6	25.7	-	0.5
SO_3	15	15	2	10	30	8.7	0.2
H_2SO_4	15	15	2	10	30	8.7	0.2
HI	-	225		-		115	5.2
I_2	21	20		5.2		-	-

The assessment of the separation distance against toxic gas release has been determined employing the heavy gas atmospheric dispersion model SLAB [11] which considers density effects of the released gases. Table 4 lists the assumptions for the calculations which were selected in a highly conservative approach. Toxic gas quantities represent total inventories in the hydrogen production system. The release is instantaneous as a gas at atmospheric conditions. Toxic gas concentrations in the control room were derived from a mass balance which considers the concentration at the intake of the ventilation system, the flow rate of the ventilation system, and the leakage rate of the control room [12].

Table 4. Analytical conditions of toxic gas concentration.

Quantity released [kg] HI – I_2 – H_2SO_4 – SO_3 – SO_2	3969 – 1094 – 288 – 933 – 431
Height of release point [m]	2.3 (for HI, I_2); 3.7 (for H_2SO_4, SO_3, SO_2)
Release mode	instantaneously as gas @ 0.1 MPa
Wind speed [m/s]	1
Atmospheric stability category	stable
Distance to NPP control room [m]	250 (for HI section); 100 (for H_2SO_4 section)
Height of intake of control room ventilation [m]	22.3
Control room air exchange rate [h^{-1}]	0.06
Time for isolation of control room [s]	10

Results of the calculations are shown in Fig. 7. Due to the assumed instantaneous release of a pressurized gas in a puff into the atmosphere, the diameter of the toxic gas cloud also grows instantaneously with the concentration values for HI and I_2 in the control room escalating immediately up to 19.3 mg/m^3. Consequently, for the HI and I_2 vapor clouds, concentrations in the control room increase within a very short time. In contrast, the concentration of H_2SO_4 cannot be depicted in the plot, since the amount of this toxic arriving at the control room was found negligible. Both SO_3 and SO_2 clouds were analyzed to approach the reactor building only after the isolation of the ventilation system; their concentration levels therefore remain at a low level.

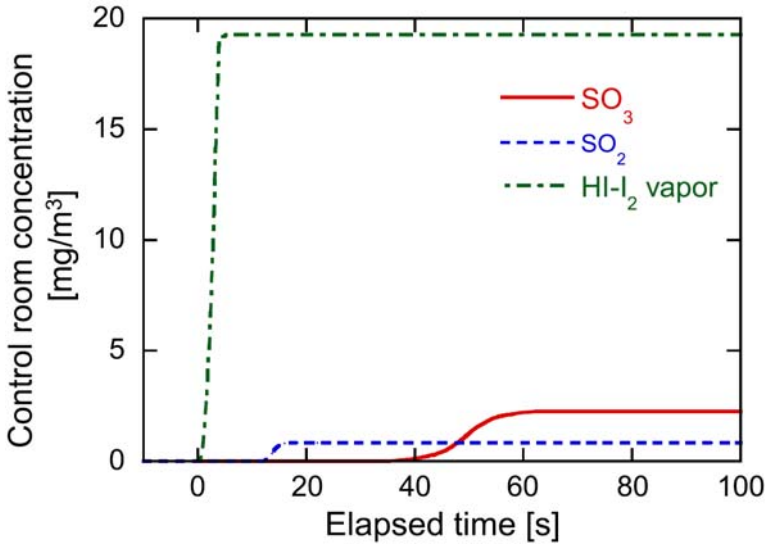

Figure 7. Evaluation results of control room concentration for hazardous chemical leakage from the hydrogen production plant

Assuming the simultaneous leakage of all hazardous chemicals from the IS plant, the evaluation indicator, which is defined as the sum of the ratios of the calculated concentration over the toxicity limit for each gas component, was assessed to be 0.81 which is below the limit value of 1.0. (A value > 1 indicates an exposure that is above the allowable concentration.) The dominant hazardous chemicals are SO_3 and I_2 which account for 15% and 75%, respectively, of the evaluation indicator. The results show that a proper safety design against hazardous chemical leakages can be ensured.

5.0 CONCLUSIONS

The Japan Atomic Energy Agency has suggested safety requirements and design considerations for a 600 MW(th) HTGR to be coupled to a hydrogen production plant based on the sulfur-iodine thermochemical cycle with the aim to contribute to the realization of large-scale nuclear hydrogen production. Analytical studies were conducted on the release, dispersive transport, and explosion of a hydrogen cloud in the atmosphere as well as on the release of toxic substances from the hydrogen production plant and their transport towards the NPP control room.

A safe operation of the nuclear power plant can be ensured by providing a set of safety requirements in order to accomplish regulatory requirements and practical design considerations when coupling the nuclear reactor with a conventionally designed chemical plant for hydrogen production. This is essentially by defining appropriate separation distances between reactor building control room and hydrogen plant against combustible gas leakages and against toxic gas leakages.

From the computer simulations, it can be concluded that a relatively small distance between the reactor plant and the hydrogen production plant should not pose any risk to the overall safety, especially if the nuclear reactor and the hydrogen plant are separated by means of an earth mound or any other type of protective wall. Despite of moving distances above 100 m if the released amount of H_2 is more than 25 kg, the H_2 mass in the flammable portion of the cloud will steadily decrease after the end of the release phase. For the 97 kg release case, maximum H_2 mass in the flammable cloud is about 45 kg, meaning that more than half of the H_2 released is at a concentration lower than the

flammability limit. A protection wall rising 2 m above hydrogen pipelines would be sufficient to cut the safe distance in half. The approximately 150 m moving distance in case of a 97 kg of H_2 release would thus be reduced to below 100 m. Such a barrier would therefore prevent the hydrogen cloud from drifting towards the reactor plant and would rather effectively contribute to its dispersion in the atmosphere. The performed research has confirmed that it is technically feasible to safely arrange the reactor plant and the hydrogen plant at a distance of 100 m from each other.

Following a successful continuous operation of the S-I pilot test facility currently under construction at the Oarai Research Establishment, it is planned to demonstrate nuclear hydrogen production utilizing heat from the HTTR test reactor [13]. The suggested safety requirements will be the basis of comprehensive examinations by and discussions with the licensing authorities in Japan.

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