LAUNCH OF THE STACY PROJECT - TOWARDS SAFE STORAGE AND TRANSPORTATION OF CRYOGENIC HYDROGEN

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ABSTRACT

World-wide efforts aim at the decarbonization of the energy sector with an increasing fraction of renewable energies in the energy mix. Energy storage technologies are required to store excess energy generated from fluctuating sources to making it accessible on demand. In this context, the large-scale storage and transportation of liquefied (cryogenic) hydrogen (LH2) can be expected to play a fundamental role in a potential future hydrogen economy due to its high storage density. Ensuring the safe implementation of related LH2 technologies is mandatory with regard to economic benefit and public acceptance.

The overall aim of the STACY project is to contribute to the safety of LH2 storage and transportation by experimentally determining fundamental safety-related parameters of hydrogen combustion not yet available for very low temperatures, developing and qualifying novel catalysts for catalytic recombiners to prevent the formation of flammable gas mixtures in case of LH2 leakages, and applying advanced numerical tools to study scenarios of potential hydrogen leakages and to assess the efficiency of mitigation measures.

In an interdisciplinary approach, STACY brings together experts from internationally recognized institutions in the fields of combustion, catalytic recombination, catalyst development, and safety assessment. The transfer of well-established safety knowhow and technologies from nuclear hydrogen safety to the field of hydrogen storage and transportation intends to overcome existing artificial borders between nuclear and non-nuclear safety research.

1.0 INTRODUCTION

The European Interest Group (EIG) CONCERT-Japan is an international joint initiative to support and enhance science, technology and innovation cooperation between European countries and Japan [1]. The 8th Joint Call on the thematic area of "Sustainable Hydrogen Technology as affordable and clean energy" was issued in 2021 aiming at developing more efficient, reliable, flexible and clean hydrogen-based technologies. The call has been based on the recognition that hydrogen technologies that are fueled by clean and affordable energy can contribute to building a better society, and help mitigate climate change and other environment impacts caused by ever-growing human reliance on energy [2]. This is in line with current world-wide efforts to decarbonize the energy sector with an increasing fraction of renewable energies in the energy mix, where hydrogen is considered to play a vital role in energy storage technologies for excess energy generated from fluctuating sources. Due to the high storage density of liquefied (cryogenic) hydrogen (LH2), the large-scale storage and transportation of LH2 can be expected to play a fundamental role in a potential future hydrogen economy.

Ensuring the safe implementation of LH2 storage and transportation technologies is mandatory with regard to economic benefit and public acceptance. Under the auspices of EIG CONCERT-Japan, the STACY project (Towards Safe storage and Transportation of Cryogenic Hydrogen) gathers experts from the fields of combustion research (CNRS-ICARE, Orléans, France), catalytic recombination for hydrogen mitigation (FZJ, Juelich, Germany), catalyst development (Kwansei Gakuin University, Kobe, Japan), and nuclear reactor safety assessment (IRSN, Fontenay-aux-Roses, France).

Large-scale liquid hydrogen storage and transportation involves several characteristics of potential safety risks similar to nuclear hydrogen safety: large hydrogen inventories, complex geometries with huge confined and semi-confined volumes, congested areas, and – in the case of maritime transportation – long and remote travel route. The decades of experience in hydrogen safety obtained from reactor safety research is virtually predestined to make a significant contribution towards safe cryogenic hydrogen.

The project results are expected to support the development of safety rules, increase public acceptance of LH2 technologies and thus have a beneficial effect on the economical and societal aspects related to LH2. Here, the Industrial Advisory Board, which is composed of experts from high-level industries and institutions, plays a pivotal role in formulating industrial needs, consulting on technical boundary conditions, and monitoring the project progress:

- Kawasaki Heavy Industries (KHI, Japan) plans to build a large liquefied hydrogen carrier to import liquefied hydrogen from Australia in the future, and is currently building a small (pilot) liquefied hydrogen carrier for verifying the CO_2-free hydrogen energy supply chain between Japan and Australia.

- Daihatsu Motor Co., Ltd. (Japan) is paying attention to hydrogen fuel as a Japanese company that provides sustainable automobiles, and is pursuing technology for storing hydrogen at high density, which is particularly applicable to small cars. Daihatsu also has high level of insight into hydrogen recombination catalysts using automotive exhaust catalysts.

- Air Liquide (France) is a world leader in gases, technologies and services for Industry and Health. For more than 40 years, Air Liquide has been developing unique expertise in the mastery of the entire liquid and gaseous hydrogen chain (production, storage, and distribution).

- Chemical Consulting Dornseiffer (CCD, Germany) holds expertise in prototyping catalytic systems especially for automotive emission control, and in designing and constructing test benches in the same business area. CCD develops and manufactures catalysts for nuclear safety research on catalytic recombiners.

- Japan Atomic Energy Agency (JAEA) is public research institute for atomic energy and related applications including hydrogen safety of power plants. Hydrogen recombination catalysts have been used in the nuclear power plants and further improvement of the catalyst is conducted by Japan Atomic Energy Agency for the proper management of hydrogen.

- EnerSys-Hawker (Germany) is a leading company for energy storage and commercial manufacturer of catalytic hydrogen recombiners.

The composition of the project consortium and advisory board allows for a blend of nuclear and non-nuclear expertise in hydrogen safety, which is intended to overcome artificial walls and enable new collaborations.

2.0 PROJECT GOALS AND WORKPLAN

The overall aim of the project is to contribute to the safety assessment of large-scale LH2 storage and transportation. To this end, it is required to perform simulation of hydrogen distribution inside complex geometry following potential hydrogen leakages. The corresponding codes need to be adapted to the specific boundary conditions and new models have to be implemented with regard to recombiner operation and combustion criteria at low temperatures. Consequently, the following technical objectives are pursued within the framework of the project:

(1) Experimental determination of fundamental safety-related parameters of hydrogen combustion not yet available for low temperatures:
Combustion of hydrogen and the phenomena behind the initiation of an explosion have been the subject of studies for several decades. While there are numerous data about hydrogen explosion at standard conditions of pressure and temperature, little is known about the explosion propensity of hydrogen at cryogenic conditions, which are responsible for a large change in the combustion properties. Among others, three fundamental combustion parameters – the flammability domain, the laminar flame speed, the expansion ratio – will be determined at temperatures between -50°C and -100°C.

(2) Development and qualification of novel catalysts for catalytic recombiners to prevent the formation of flammable gas mixtures in case of LH2 leakages:
Dilution and ventilation of hydrogen releases in closed or semi-confined environments are the most efficient means to avoid the formation of flammable mixtures. However, in specific low-ventilated areas, e.g. on a maritime hydrogen carrier, catalytic recombiners can provide a relevant hydrogen sink. While recombiners have been qualified for elevated temperatures and pressures, no knowledge exists on the operational performance at low temperatures. The specific objective is to develop and qualify a novel catalyst to operate under the typical conditions of LH2 applications.

(3) Application of advanced numerical tools to study scenarios of potential hydrogen leakages and assessing the efficiency of mitigation measures:
Although hydrogen leakages and formation of flammable gas mixtures has been studied since a long time, the specific conditions of LH2 applications, such as low temperature, specifics of the geometry, natural ventilation, still represent challenging boundary conditions. The specific objective is to apply well-proved codes on the simulation of hydrogen distribution and mixing to identify potential modelling gaps, study potential accident scenarios and provide information on potential boundary conditions and locations for additional mitigation measures.

In order to reach the specific goals, the project activities are allocated to five work packages (WPs), which are interlinked as shown in Fig. 1. In WP 1, the atmospheric boundary conditions of LH2 storage and transportation applications – e.g. maritime LH2 carriers – are identified through scenario analyses. The experimental and numerical investigations on combustion fundamentals (WP 2) as well as the qualification of catalysts and catalytic recombiners (WP 3) will consider these conditions. The facilities used at the laboratories at CNRS-ICARE, FZJ and KGU will be adapted accordingly. Results in terms of fundamental combustion data and numerical correlations describing the performance of catalytic recombiners will be implemented in the updated safety assessment methodology for LH2 storage and application (WP 4). The Industrial Advisory Board will be involved in the progress of these WPs in order to provide relevant application data and geometry information, discuss catalyst features and recombiner design, and contribute hydrogen safety regulations and standards.

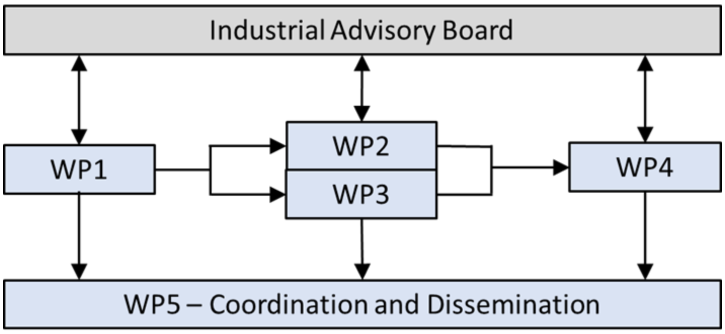

Figure 1. Interaction of work packages

3.1 WP 1 – Critical review and scenario identification

The WP 1 objective is to provide an overview of the existing methodologies and practices to assess the safety of LH2 storage and transportation. To this end, a critical review of typical, qualitative and quantitative, methodologies used to assess the hydrogen risk is performed by the Institute de Radioprotection et de Sûreté Nucléaire (IRSN). The qualitative methodologies are mainly based on the feedback from past accidents and existing knowledge about the hazards. The ranking of the scenarios is performed then qualitatively by combining the categorization of probabilities and consequences with risk acceptance categories in a matrix form that helps identifying scenarios with a higher priority than a set of risks collected.

The quantitative methodologies, as Hazard Identification (HAZID), Hazard and Operability Analysis (HAZOP) and Failure Modes and Effects Analysis (FMEA) use a systematic assessment to identify hazards and problem areas associated with plant, system, operation, design and maintenance. Probabilistic Risk Assessment (PRA) and Quantitative Risk Assessment (QRA) permit in addition to quantify the probability of an identified event. Deterministic approaches are then performed to ensure that the worst-case scenarios can be handled regarding the risk acceptance criteria for the relevant installation.

The previous methodologies allowed establishing safety rules, as the separation of the LH2 containing facilities from roads, buildings, or runways, the ventilation for enclosed areas, the preclusion of air ingress, automated system shutdowns, confinement and control of large-scale spills, or the use of non-sparking electric devices. The uses of passive systems as catalytic recombiners have not been considered yet as possible mitigation means for LH2 facilities.

Moreover, these methodologies are based mainly on the use of “simple engineering” tools considering homogenous conditions to evaluate maximum pressure, as P_{AICC} and P_{CJ} induced respectively by adiabatic isochoric complete combustion and detonation. Dynamic pressure loads, generated by accelerated flame and leading to more serious damages are not addressed in such tools. The use of CFD tools can help addressing atmosphere heterogeneity and assessing dynamic loads induced by flame acceleration.

3.2 WP 2 – Combustion fundamentals

The work program allocated in WP 2 aims at the determination of fundamental combustion parameters to the evaluation of low temperature hydrogen explosions. Experimental and simulation studies will be performed by CNRS-ICARE at low temperature (between -100°C and -50°C). The fundamental results will be incorporated into the numerical analyses in WP 4.

Flammability limits are a pre-requisite to any explosion scenario and safety analysis. Their knowledge with the variation of the thermodynamic conditions and composition will be investigated experimentally using spark induced ignition with an adjustable energy and simulated using detailed chemistry.

The second pillar parameter is the laminar flame speed which embeds both the transport properties and the chemistry. It will be determined in a spherical bomb with a central ignition. The use of a synchronized high-speed imaging and dynamic pressure transducer will allow to determine the stretched laminar flame speed, the maximum pressure rise, the identification of the onset of instabilities and characterize the self-acceleration of the flame (Fig. 2).

The results will be simulated using detailed chemistry models. The thermodynamic parameters will be evaluated based on ab-initio calculation as the estimation of equilibrium properties depends on accurate thermodynamics. Following the validation of the detailed chemistry, the global activation energy can be derived and the Zeldovich number will be determined for these low temperature conditions.

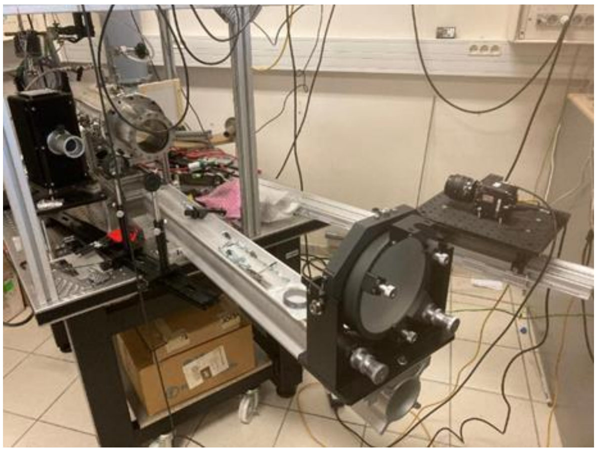

Figure 2. Cylindrical vessel for low temperature combustion at ICARE

These experimental data will be used to validate a detailed chemical kinetic mechanism of hydrogen oxidation by extending its validity to very low temperature. In a next step, it will be used to deduce fundamental parameters, as the flammability limits, the minimum ignition energy, as the expansion ratio, and to estimate the detonation characteristics such as the detonation cell size which in turns is used to assess the detonability of cryogenic hydrogen.

3.3 WP 3 – Catalytic recombination

WP 3 aims at developing a catalyst for operation under low-temperature conditions and studying the operational behavior of a corresponding catalytic recombiner. Relevant boundary conditions will be obtained from the scenarios studied in WP 1.

3.3.1 Catalyst development

Research at Kwansei Gakuin University (KGU) focuses on the catalytic activity at extremely low temperatures, assuming that liquid hydrogen leaks. For safety reliability, it is essential to quantitatively evaluate the catalytic performance in a combination of inferior conditions. We’ll evaluate catalytic activity under adverse conditions, especially after long-term exposure to the atmosphere and humidity. In addition, when the catalyst is exposed to the atmosphere for a long period of time, the surface of the precious metal is usually covered with an oxygen layer, and the catalyst tends to be in a temporary dormant state. It is also necessary to quantify those effects in lab-scale experiments.

KGU is responsible for catalyst development, preparation, and lab-scale testing (Fig. 3). The work involves graduate students. Various catalyst materials can be designed. In addition to ordinary precious metal impregnated and supported on the surface, there are unique catalysts arranged as cations in the perovskite crystal structure lattice. These catalysts are known as “the intelligent catalysts” for automotive emissions control due to their ability to self-heal in real-world environments. They can be prepared in various shapes such as powder, pellet, bead, and honeycomb. It is also possible to tailor these catalysts to be hydrophilic or hydrophobic.

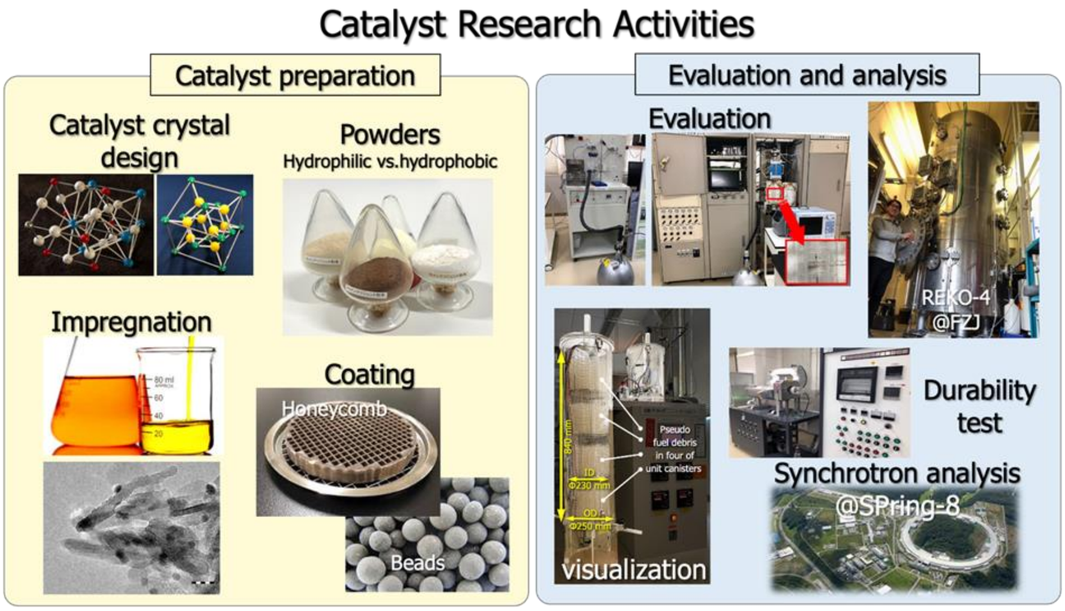

Figure 3. Catalyst research at KGU

Catalysts are then analyzed at the order of molecules and atoms using SPring-8, a third-generation synchrotron radiation facility. In addition to the lab at KGU, the activity will be evaluated in the REKO-4 pressure vessel in collaboration with FZJ as described below.

3.3.2 Recombiner qualification

A catalytic recombiner is considered to be a passive hydrogen mitigation device, as it does not need external energy in order to activate. It is self-starting and self-feeding and is used to mitigate the risk of hydrogen accumulation in unintended hydrogen release scenarios. Catalytic recombiners are state-of-the-art devices for hydrogen risk mitigation in nuclear power plants (NPPs) and there is an increasing interest in potential applications in hydrogen technologies.

A numerical model to describe the operational behavior of catalytic recombiners will be developed in WP 3 to be used in scenario simulations (see WP 4). For this purpose, recombiner operation under scenario-typical conditions is investigated in the REKO-4 pressure vessel (Fig. 4) operated at Forschungszentrum Juelich (FZJ). The transient behavior (catalyst light-off and recombiner start-up) as well as quasi-steady-state recombination rates will be determined for relevant boundary conditions [3].

The research program involves recombiners with catalysts developed within the STACY program (see section 3.3.1) as well as commercial products. Figure 4 (right, top) shows a Hydrogen Eliminator by Hawker EnerSys used in maritime applications that is considered in the on-going test program. The compact design, which allows installation in restricted spaces, is fundamentally different from those that are typically installed in nuclear power plants. At the same time, the expected boundary conditions in LH2 release scenarios in maritime transportation vary considerable from those in a nuclear power plant accident.

Figure 4. REKO-4 test vessel (left), EnerSys Hawker Hydrogen Eliminator (right, top), Recombiner installed inside the test vessel (right, bottom)

3.4 WP 4 – Application: Safety methodology assessment

WP 4 aims to improve the LH2 risk assessment methodology with the objective to measure the efficiency of the implementation of catalytic recombiners. For this purpose, a methodology based on the use of empirical correlations and CFD tools, already developed to assess the hydrogen risk in nuclear power plants, will be used. The empirical correlations permit to identify the flammable clouds and their propensity to induce flame acceleration in case of ignition. The CFD tools simulate the gas mixing and evaluate the pressure and temperature loads considering the geometry details.

The methodology then used is composed on several steps: (1) modeling the facility using meshes taking account the geometric details, (2) simulating hydrogen dispersion, (3) identifying flammable clouds and assessing the propensity of flame acceleration, (4) evaluating pressure and temperature loads induced by combustion and (5) assessing the consequences on the induced pressure and temperature on facility structures.

In this context, the benefit of considering catalytic recombiners will be assessed and discussed. The results from WP 2 (combustion criteria) and WP 3 (numerical recombiner models) will fill existing knowledge gaps.

3.5 WP 5 – Coordination and dissemination

According to the rules of projects funded by EIG CONCERT-Japan, networking between European and Japanese institutions are especially emphasized. It is the role of WP 5 to ensure corresponding activities in addition to the usual tasks involved in project coordination and dissemination of the project results.

The first project year's most relevant networking event was the first STACY symposium held at Kobe/Japan under the endorsement of Kwansei Gakuin University (Fig. 5). Located at the Kobe International Conference Center, the program included lectures given by project partners and members of the Industrial Advisory Board.

Figure 5. Group photo of participants of the 1st STACY Symposium (top), Organizing Committee: Tanaka Laboratory Students, KGU (bottom)

The symposium program involved a technical tour for the general public, courtesy of Kawasaki Heavy Industries, Ltd. The tour involved the liquefied hydrogen receiving terminal (Fig. 6, left) of Suiso Frontier, the world's first liquefied hydrogen carrier, and a hydrogen co-generation system, the world's first delivery of energy and heat in an urban area generated using a gas turbine fueled by 100 % hydrogen (Fig. 6, right).

Figure 6. Liquefied hydrogen receiving terminal (left), Hydrogen co-generation system (right)

Further symposium events included the organization of a Young Generation Seminar involving the students participating in the project as well as students from the hosting institution at KGU. A tour of the large synchrotron radiation facility "SPring-8" was also held as a post-symposium event.

Networking activities are involving collaboration with other projects working in the field of LH2 safety, such as SUSHy (Sustainability and cost-reduction of hydrogen stations through risk-based, multidisciplinary approaches), ELVHyS (Enhancing safety of liquid and vaporized hydrogen transfer technologies in public areas for mobile applications), and ESKHYMO (Améliorer les connaissances en matière de sécurité pour les mesures/modélisations de l'hydrogène en phase cryogénique).

Furthermore, the project has been presented at the biennial Research Priorities Workshop of the International Association HySafe in late 2022.

4.0 SUMMARY AND CONCLUSIONS

Liquefied hydrogen is expected to play a future role as an economical and high-density storage and transportation technology. The STACY project aims at providing knowledge on the safe LH2 usage to support hydrogen as an affordable, clean and sustainable source of energy. By tackling safety-relevant issues related with the storage and transport of cryogenic hydrogen, the project contributes to facilitate the introduction of LH2 storage and transportation technologies. Further development of safety assessment methodologies will provide more mature tools to support the safe implementation of hydrogen technologies.

The project tackles relevant safety questions of LH2 storage and transportation. Safety-relevant parameters for hydrogen combustion not yet available in literature will be determined for low temperature ranges. The results from the combustion experiments will provide fundamental data to be published for the use by experts around the world to better understand and assess the combustion risk in LH2 storage and transportation. Furthermore, the project brings innovation through the transfer of proven recombiner technology from the field of nuclear hydrogen safety to LH2 storage and transportation. The adaptation to the new boundary conditions represents a first-time application of catalytic recombiners in cold environment, and provides pre-requisite to safe hydrogen transportation expected to be transferred to other hydrogen applications such as e.g. underground storage. Promising areas of application are expected to be identified by the Industrial Advisory Board. It is expected that the results of catalyst development and qualification will enable the partners and participating industrial companies to project prototypes of catalytic recombiners for application in the field of hydrogen storage and transportation.

Bringing well-established safety knowhow and technology from nuclear hydrogen safety to hydrogen storage and transportation in the non-nuclear energy sector represents a knowledge transfer across artificial borders, contributing to tear down traditional walls between nuclear and non-nuclear research. We expect to inspire the participating students and young researchers to take an unbiased view on relevant issues of hydrogen technologies. The Young Generation Workshops in three countries involving national and international students will broaden their minds and fuel the spirit of international collaboration. The multiple dissemination activities within the project involving world-wide connected networks such as the International Association HySafe and international projects are expected to ensure reaching a wide audience beyond Europe and Japan.

The strong expertise of the European partners in the field of nuclear hydrogen safety enables relevant technology transfer to non-nuclear hydrogen technologies. Especially the introduction of catalytic recombiners, being relatively unknown in non-nuclear applications, can be expected to generate new options for safety concepts in hydrogen technologies in Japan. In return, the strong expertise of the Japanese industry being world leader in the technology of maritime LH2 carriers can be expected to stimulate application-oriented research by the European partners.

The multi-lateral collaboration will be a unique opportunity for the students and young researchers involved to engage in intercultural exchange and broaden their intellectual horizons. The Young Generation Workshops and related social events will bring abundant opportunities for intercultural networking with their peers.

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REFERENCES

1. https://concert-japan.eu
2. EIG CONCERT-Japan, Joint Call on Sustainable Hydrogen Technology as Affordable and Clean Energy – Call text and national and regional regulations, 2021.
3. Krenz, S.R., Reinecke, E.-A., Tanaka, H., Bentaib, A., and Chaumeix, N., Experimental characterization of the operational behaviour of a catalytic recombiner for hydrogen mitigation, Proc. International Conference on Hydrogen Safety, Québec, Canada, September 19-21, 2023.