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**International Energy Agency
Hydrogen Implementing Agreement**

Annex 31 - Hydrogen Safety

1. Description of the Technical Sector

The lack of operating experience with hydrogen energy systems in consumer environments continues as a significant barrier to the widespread adoption of these systems and the development of the required infrastructure. During recent years, a significant international effort has been initiated for the development of necessary codes and standards required for the introduction of these new systems. However, such codes and standards are usually developed through operating experience in actual use that is accumulated over time. Without such long term experience, there is a natural tendency for such codes and standards to be unnecessarily restrictive to ensure that an acceptable level of safety is maintained. One possible effect is to hinder the introduction of hydrogen systems and thus the operating experience upon which future infrastructure is developed. Likewise, this lack of operating data impacts other areas such as insurance cost and availability and public acceptance.

Although an understanding of hydrogen's physical properties is well established, and many experimental efforts have attempted to fully characterize the risks and hazards related to hydrogen, the actual risks and hazards can only be determined within the context of real systems and real operating experience. Previous experience with hydrogen has not been with systems that will interface with consumers, but in controlled environments using trained personnel.

Task 31, Hydrogen Safety was approved for a three year term by the IEA Hydrogen Implementing Agreement in October 2004 and after being extended for an additional three years will completed in October 2010. The results achieved by this collaboration were significant, but the experts unanimously agreed that more work is needed and this can best be accomplished through a new task on hydrogen safety. This annex is the logical follow-on activity to Task 31 and will build on the results of Task 19 to alleviate the issues of hydrogen safety and the lack of uniform Regulations, Codes and Standard to reduce or eliminate these as a barrier to the widespread commercial adoption of hydrogen energy systems.

2. Objective

The objective of this Task is to develop quantitative risk analyses, testing methodologies and data, and other information that will facilitate the accelerated adoption of hydrogen systems.

3. Means

(a) The objective shall be achieved by the Participants in the following four subtasks:

Subtask A - Physical Effects Knowledge Gaps

This objective of this subtask is to address knowledge gaps related to the physical and chemical properties of hydrogen as a gas or a liquid to increase the knowledge base on hydrogen properties relevant to safety issues. The task will tackle issues pertaining to sources, release phenomena, dispersion processes, ignition and combustion modes. Experimental, theoretical and numerical analyses are covered by this task.

Participants shall achieve this objective through the following activities:

Working group A1: Release Phenomena

- Source characterization and modeling;
- Dispersion behavior;
- Characterization of surface effects on Jet releases;
- Flammability, combustion and toxicity of gas mixtures; and
- Liquid hydrogen release behavior, including the dispersion behavior of low temperature hydrogen vapor clouds.

Working group A2: Ignition and combustion

- Ignition of hydrogen releases (issues & modeling) to include ignition mechanisms, ignition probability studies and self-ignition issues
- Behavior of Jet flames, e.g., thermal radiation issues in the presence of a crosswind (experiments and theory) and surface effects on flame jet propagation.
- Effects of overpressure and explosions.

Working group A3: Assessment of quantitative tools for hydrogen safety

- CFD validation Matrix
- Engineering correlations
- Turbulence modeling issues

Subtask B – Hydrogen Storage Systems and Materials Compatibility

The objective of this Subtask is to identify and characterize safety related issues related to materials compatibility and other issues for various hydrogen storage approaches.

Participants shall achieve this objective by focusing on the following technical areas:

Safety, reactivity and risk mitigation of hydrogen storage in different forms:

Compressed hydrogen gas (CH₂), liquefied (cryogenic) hydrogen (LH₂) and solid-state hydrogen storage in metal hydrides, such as NaAlH₄, MgH₂, Mg(NH₂)₂+MgH₂+2LiH), chemical hydrides, such as NH₃BH₃, AlH₃ and adsorbents such as AX-21 activated carbon and MOF-5.

Safety and risk mitigation measures of hydrogen storage systems and system interfaces for mobile and stationary applications:

The mobile application includes on-board vehicular storage systems and other advanced portable devices for specialized applications. The stationary systems include hydrogen fueling stations, stationary fuel cells that use hydrogen as the feedstock, auxiliary power systems (APUs), etc. System interfaces include hydrogen dispensing systems and safety hazards arising from accidental fast filling, postulated intrusion of impurities and/or moisture (through hydrogen dispensing devices) during hydrogen charging for vehicular applications, etc.

Investigation of on-board vehicular storage systems materials compatibility issues:

Examples include hydrogen storage vessels (Type-III and Type-IV vessels), balance of plant (BOP) components (e.g., heat exchanges, pumps, valves, piping), etc. Hydrogen permeation, hydrogen embrittlement, hydrogen attack of Type-III vessel's metal liners and subsequent hydride embrittlement, stress corrosion cracking, liner delamination, thermal fatigue, mechanical

fatigue, strain failure of vessel composite materials, low-temperature embrittlement, hydrogen attach of liner materials and blistering phenomenon are also examples of focus areas for this activity.

Enabling technologies for fire suppression systems and fire suppression agents compatible with hydride storage material:

This activity includes fire suppression systems' design, performance and reliability assessment. Chemical characterization and validation tests of fire suppression agents compatible with fires from energetic materials such as metal hydrides and predictive heat transfer models for fire suppression devices dedicated to solid-state hydrogen storage are among the scope of interest under this activity.

Safety categorization framework for hydrogen storage materials and associated life cycle impact assessment (LCIA):

The impact assessment includes potential environmental damage and human health damage resulting from using specific solid-state hydrogen storage materials. The life cycle assessment includes manufacturing, on-board use and end-of-life (EOL) disposal or recycling of the hydrogen storage material.

Subtask C - Early markets: risk identification and hazard analysis

The objective of this Subtask are to tailor existing safety assessment methods, data, and use of prevention and mitigation features need to address the specifics of early markets due to lack of data and understanding of specific phenomena, and to communicate this information to relevant stakeholders within international codes & standards development activities to ensure those requirements are risk-informed and evidence-based.

Participants shall achieve this objective by the conduct of the following activities:

Failure (frequency) statistics of new hydrogen applications.

The scope will target emerging hydrogen markets. Initially the focus will be on hydrogen forklift operations in US and Canada using a mutually agreed template for data collection consistency. Other available reliable data sources of failure statistics on other applications will not be overlooked. Collected data will then be used in Bayesian statistical analysis to derive credible correlations for the use in quantitative risk assessment.

Improvements in risk assessment and hazard analysis methodologies.

The scope will include monitoring and proposing further developments in risk assessment methodologies. Any related publicly available risk assessment studies and specifically QRAs will be reviewed. Improved methods to address known weaknesses in existing risk assessment activities will be identified. In particular, methods for addressing uncertainty in the data and models will be addressed. Ultimately, it would be desirable to establish an international standard for performing QRAs of hydrogen facilities.

Systems safety analysis of hydrogen applications.

The scope will include both qualitative and quantitative risk assessments of real world hydrogen systems and equipment with a purpose of establishing their suitability for intended operation (i.e. strengths and weaknesses in design) and identifying potential gaps in existing RCS pertaining to those applications. At this stage, the following applications are being targeted: a) transportation /

mobility sector; b) forklifts; c) stationary fuel cell systems; d) renewable energy systems & APUs; e) distribution and refueling infrastructure.

Prevention and mitigation

The scope will include evaluation of the following prevention and mitigation measures: a) sensors; b) barriers / walls; c) safety distances based on Subtasks A and B contributions; d) visual inspection, testing and maintenance schedules; e) safety education and training. The evaluation will identify which features are most effective in reducing risk. The cost/benefit of different prevention and mitigation features will also be evaluated.

RCS development support (knowledge analysis and recommendations) to relevant ISO and IEC standard development activities.

The scope will include provision of risk-informed and evidence-based information to and participation in the relevant ISO and IEC technical committees and working groups. It is anticipated that Task experts participating in the work of those committees will provide regular updates on the current status and most critical issues under discussion to the Task membership, and will communicate received feedback to relevant committees.

Subtask D: Knowledge analysis, dissemination and use (Subtask Leader: Steven Weiner, PNNL)

The objective of this Subtask is to enhance databases and websites that have been integral to the work products and accomplishments of Task 19.

Participants shall achieve this objective through the following activities:

Hydrogen incident reporting, analysis and lessons learned

Two databases play unique and complementary roles in collecting and analyzing hydrogen-related safety event information: (1) Hydrogen Incident Reporting and Lessons Learned Database (“H2incidents.org”) and (2) Hydrogen Incident and Accident Database (HIAD). Collaborations will be developed to capitalize on the unique attributes of these databases for the purposes of ensuring that data, information and knowledge from hydrogen safety events is broadly disseminated and used to achieve the overall goals of Task 31.

Hydrogen Safety Best Practice

“H2bestpractices.org” is a publically available manual and website which is being maintained and enhanced under support of the U.S. Department of Energy. Collaborative opportunities will be sought. (Participants: PNNL, lead, others)

Expanding the Hydrogen Safety Bibliographic Database

Continuing development of the HyTEX Database

This database was developed under Task 19/Subtask B to facilitate the posting, sharing and use of experimental and hydrogen safety-related data. It contains details of experimental programs that are planned, ongoing and completed. The need to ensure that the database is current and valuable will form the basis for future work.

Developing training materials for regulators and public safety officials

Individuals and organizations need to assess the safety aspects and certify an increasing number of installations of hydrogen-related technologies in public areas, companies or universities. In Europe, leading players are collaborating to produce and disseminate up-to-date content for hydrogen safety training with the support of the European Commission.

Risk Communications

The modeling of accidents/incidents including the development and use of visualization tools can play an important role in understanding what happened, preventing/mitigating future occurrences and communicating the risks. Collaborative opportunities will be sought and encouraged.

(b) Subtask Leaders. A Subtask Leader shall be designated for each of the foregoing subtasks:

(1) Selection of Subtask Leaders

The Subtask Leader shall be a Participant who provides to the Subtask a high level of expertise and undertakes substantial research and development in the field of the Subtask. The Subtask Leaders shall be proposed by the Operating Agent, and designated by the Executive Committee acting by unanimity. Changes in the Subtask Leaders may be agreed to by the Executive Committee, acting by unanimity of the Participants.

Proposed Subtask Leaders

Subtask A: Pierre Benard, University of Trois Riviere, Quebec, Canada

Subtask B: John Khalil, United Technologies Research Center, USA

Subtask C: Mr. Andrei Tchouvelev, Stuart Energy, Canada

Subtask D: Steven C. Weiner, PNNL, USA

(2) Duties of Subtask Leaders

The Subtask Leader for each of the foregoing tasks shall:

- Coordinate the work performed under that Subtask;
- Assist the Operating Agent in preparing the detailed Programme of Work;
- Organize and chair meeting as part of the Task meetings or as independent meeting as deemed appropriate by the Participants;
- Lead the experts in the production of technical reports and be responsible for the final editing; and
- Provide the Operating Agent with the annual report of Subtask activities.

(c) Technical Advisory Committee. The Participants shall establish a Technical Advisory Committee (the "Technical Advisory Committee") consisting of Subtask Leaders and the Operating Agent or their respective designees. The Technical Advisory Committee shall assist the Operating Agent in the coordination of the Task and advise the Operating Agent on the performance of the Task.

4. Results

The collective effort of this Task will result in the following outputs:

Subtask A:

- Experimental characterization of hydrogen releases, ignition, jet fires and explosions.
- Predictive theoretical tools and their validation in the form of CFD models and engineering correlations.
- Reports, white papers, conference presentations and publications in scholarly journals.
- Validation matrix
- Engineering correlations report

Subtask B:

- Experimental characterization and risk mitigation insights such as materials reactivity tests and prototypes, solid-state dust cloud explosion tests, sensitivity of energetic hydrogen storage materials to mechanical impact, etc.
- Predictive theoretical tools such as CFD models, simulations, etc.
- Probabilistic risk assessment (PRA) framework for accident scenario development using formal PRA tools and methods such as fault tree and event tree analysis.
- Safety categorization framework for hydrogen storage materials and life cycle impact assessment (LCIA). The impact assessment includes potential environmental damage and human health damage resulting from using specific solid-state hydrogen storage materials.
- Reports, white papers, conference presentations and publications in scholarly journals.

Subtask C:

- Topical Reports or compiled summaries for each of the activities conducted under Subtask B: failure statistics of new hydrogen applications, Improved methods to address known weaknesses in existing risk assessment activities, and qualitative and quantitative risk assessments of real world hydrogen systems and equipment with a purpose of establishing their suitability for intended operation (i.e. strengths and weaknesses in design) and identifying potential gaps in existing RCS pertaining to those applications.

Subtask D:

- Topical Reports Targeted Information Packages for stakeholder groups. Such reports would be summary reports of the data and results of Subtasks A, B, and C, and would only contain information approved by the participants. There would be a number of key products that would be of significant value in accelerating widespread use of hydrogen. It is expected that the collaborative program would facilitate the dissemination of operating information upon which others could base the development of infrastructure in their individual countries.

5. *Time Schedule*

This Annex shall remain in force for a period of three years. This Annex shall enter into force on the 1st of November 2010, and remain in force until the 31st of October 2013. Within the limits of the term of the Agreement, this Annex may be extended by two or more Participants, acting in the Executive Committee, and shall thereafter apply only to those Participants.

6. *Responsibilities of the Participants*

In addition to the obligations enumerated in Article 7²² of this Agreement:

- (a) Each Participant shall provide the Operating Agent with detailed reports on the results of the work carried out for each Subtask;
- (b) Each Participant shall collect, assess and report to the Operating Agent data on Hydrogen Safety; and

²²

Article number refers to Model "Umbrella" Implementing Agreement.

- (c) Each Participant shall participate in the editing and reviewing of draft reports of the Task and Subtasks.

6. *Specific Obligations and Responsibilities of the Operating Agent*

In addition to the obligations enumerated in Articles 4 and 7 of this Agreement, the Operating Agent shall:

- (1) Prepare and distribute the results mentioned in paragraph 4 above;
- (2) Prepare joint assessments of research, development and demonstration priorities for Hydrogen Safety;
- (3) At the request of the Executive Committee, organize workshops, seminars, conferences and other meetings;
- (4) Prepare the detailed Programme of Work for the Task in consultation with the Subtask Leaders and the Participants and submit the Programme of Work for approval of the Executive Committee;
- (5) Propose and maintain a methodology and a format for the submission of information on Hydrogen Safety which is collected by the Participants as described in paragraph 3 above;
- (6) Provide, at least semi-annually, periodic reports to the Executive Committee on the progress and the results of the work performed under the Programme of Work;
- (7) Provide to the Executive Committee, within six months after completion of all work under the Task, a final report for its approval and transmittal to the Agency;
- (8) In co-ordination with the Participants, use its best efforts to avoid duplication with activities of other related programmes and projects implemented by or under the auspices of the Agency or by other competent bodies;
- (9) Provide the Participants with the necessary guidelines for the work they carry out with minimum duplication;
- (10) Perform such additional services and actions as may be decided by the Executive Committee, acting by unanimity.

7. *Information Protection and Limited Report Dissemination*

Although it is recognized that in order to achieve its goal of accelerating the widespread use of hydrogen, methods, data and other results developed during the course of Subtasks A and B should be publicly disseminated as soon as practicable, such information will be held confidential for a period of two years unless the Participants agree to its release at an earlier date. Summary reports of the evaluations and conclusions will be delivered to the Executive Committee as they are completed, and will be held confidential by the member countries of the Executive Committee, unless or until all parties agree to make them publicly available.

8. *Funding*

(a) The Participants, Subtask Leaders and Operating Agent shall bear the costs they incur in carrying out their work under this Task, including the costs of preparing and transmitting reports and travel expenses.

(b) The costs of organizing meetings and workshops shall be borne by the host Participant, excluding the travel, lodging and meal costs of the experts.

9. *Operating Agent*

William Hoagland, WHA, LLC, Boulder, Colorado, USA, acting through Natural Resources Canada (Canada) and Sandia National Laboratories (USA) is designated as Operating Agent. In that capacity, he will be equally supported by those organizations and accepts the rights and powers and commits to carry out the obligations and functions of the Operating Agent as provided in the Agreement.

10. *Information and Intellectual Property*

At the outset of this task, it is not anticipated that any proprietary for intellectual property will be created by this task. However it is understood that some information shared may be sensitive and inappropriate for public release. Nevertheless, experts should be comfortable sharing such information and under the previous collaboration, the participating experts developed a very strict policy for reviewing any and all information and agreed that no information will be made public until a consensus have been reached.

11. *Participants in this Annex*

It is anticipated that, as a minimum, the following member countries of the Hydrogen Implementing Agreement will participate in the annex:

<u>Country</u>	<u>Subtask</u>			
	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
Canada	✓	✓	✓	✓
EC (JRC)	✓	✓	✓	✓
France	✓	✓	✓	✓
Greece	✓			
Germany	✓	✓	✓	✓
Italy	✓	✓	✓	✓
Japan	✓	✓	✓	
Norway	✓	✓	✓	✓
Netherlands	✓	✓	✓	✓
UK	✓		✓	✓
USA	✓	✓	✓	✓

**IEA Hydrogen Implementing Agreement
Task 31 Hydrogen Safety
For the period
November 1, 2010 through October 31, 2013**

Work Plan

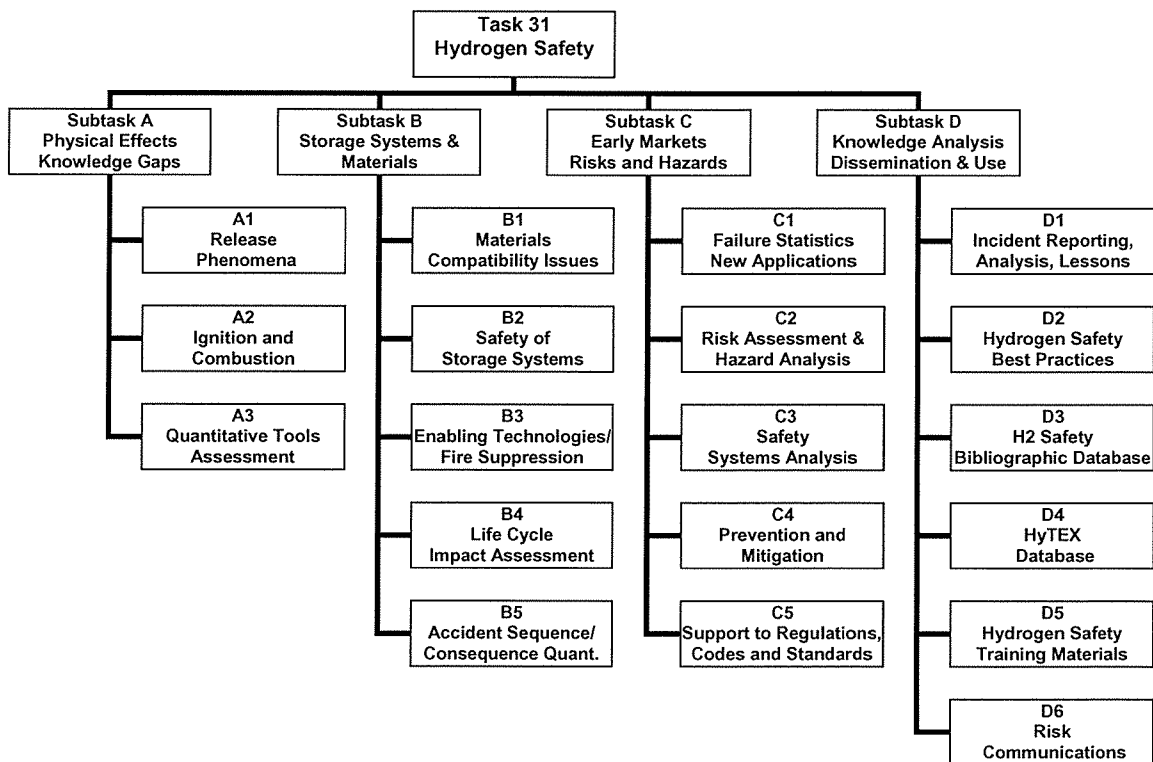
1.0 Goals and Objectives

The Goal of the Hydrogen Safety Task is to develop and conduct effective risk management techniques, testing methodologies, test data, and targeted information products that will facilitate the accelerated adoption of hydrogen systems.

The specific objectives of this task are:

- to develop testing methodologies around which collaborative testing programs can be conducted;
- to collect information on the effects of component or system failures of hydrogen systems; and
- to use the results obtained to develop targeted information packages for selected hydrogen energy stakeholder groups.

1.1 Task Organization Chart



2.0 Brief Description of Subtasks

(See Appendix 1 for abbreviations for participating organizations)

Subtask A - Physical Effects Knowledge Gaps (Subtask Leader: Pierre Bénard, UQTR)

This subtask will address knowledge gaps on the physical and chemical properties of hydrogen as a gas or a liquid in support of the work performed in the other subtasks and to increase the knowledge base on hydrogen properties relevant to safety issues. The task will tackle issues pertaining to sources, release phenomena, dispersion processes, ignition and combustion modes. Experimental, theoretical and numerical analyses are covered by this task.

Activities

A.1 Working group: Release phenomena (Lead: Thomas Jordan, KIT)

A.1.1 Source characterization and modeling (*Participants: University of Ulster, Air Liquide, UQTR, SNL*)

This activity will address issues pertaining to PRD's (pressure relief devices), the shape of orifices, and notional approximations.

A.1.2 Dispersion behavior (*Participants: Air Liquide, CEA, JRC, UQTR, HSL, KIT, UNIPI, UU, GexCon, SNL, Demokritos, NREL*).

This broad project includes simulations and experimental studies on the dispersion of hydrogen (post-release and pre-ignition).

- Enclosed areas and ventilation (simulations, modeling and experiments)
- Large scale gaseous releases (simulations and experiments)
- Obstruction and dispersion
- Release rate issues
- CFD Validation

A.1.3 Characterization of surface effects on Jet releases. This activity is a direct continuation of the work of task 19 and involves the further characterization of the knowledge base on jet releases. (*Participants: UQTR, SNL, UNIPI, AVT, HSL, KIT*)

A.1.4 Gas mixtures: flammability limits, combustion and toxicity. This activity addresses gas mixture issues which impact the use of hydrogen as an energy vector (such as the dispersion properties of hydrogen-natural gas mixtures (used as fuel) and of mixtures of hydrogen and dangerous gases such as CO and ammonia, which are used in the context of quality control of fuel cells.

- Natural gas – hydrogen mixtures
- H₂-NH₃ + H₂-CO mixtures

(*Participants: UQTR, PISA*)

A.1.5 Liquid hydrogen release behavior

This activity addresses the behavior of liquid hydrogen releases, including the dispersion behavior of low temperature hydrogen vapor clouds. (*Participants: Sandia, HSL, Demokritos, GexCon*)

A.2 Working group A2: Ignition and combustion (Lead: Dag Bjerketvedt, Telemark University)

A.2.1 Ignition of hydrogen releases (issues & modeling) to include ignition mechanisms, ignition probability studies and self-ignition issues (*Participants: Sandia, HSL, U. of Ottawa, JARI, KIT*).

A.2.2 Behavior of Jet flames, e.g., thermal radiation issues in the presence of a crosswind (experiments and theory) and surface effects on flame jet propagation. (*Participants: AVT, UQTR, HSL, Sandia, GexCon, University of Ulster, KIT*).

A.2.3 Effects of overpressure and explosions. (*Participants: Telemark, GexCon, Air Liquide, SNL, KIT, JARI*).

A.3 Working group A3: Assessment of quantitative tools for hydrogen safety (Lead: Pierre Bénard, UQTR)

The objectives of this task are (1) establish a recommended set of experimental data for validation of hydrogen CFD simulations,(2) to establish compendium of existing engineering models including models developed by the HIA task 19 and (3) propose optimal parameters for models used in CFD simulations . This task will complete preliminary work performed within the context of task 19. It crosses over with several activities of working groups A1 and A2. Its objective is closely linked with those of subtask D (particularly D6). (*Participants: UQTR, others*)

A.3.1 CFD validation Matrix (*Participants: KIT (lead), SNL, NREL, GexCon, Air Liquide, JRC, CEA, Telemark U.*)

A.3.2 Engineering correlations (*Participants: UQTR (lead), KIT, SNL*)

A.3.3 Turbulence modeling issues (*Participants: UQTR, KIT*)

A.4 Deliverables/Products

1. Experimental characterization of hydrogen releases, ignition, jet fires and explosions.
2. Predictive theoretical tools and their validation in the form of CFD models and engineering correlations.
3. Reports, white papers, conference presentations and publications in scholarly journals.
4. Validation matrix (A3)
5. Engineering correlations report (A3)

Subtask B – Hydrogen Storage Systems and Materials Compatibility (Subtask Leader: John Khalil, UTRC)

During the period November 2010 through October 2013, Subtask B plans to focus on the following

technical areas:

- **Safety, reactivity and risk mitigation of hydrogen storage in different forms:**

Compressed hydrogen gas (CH₂), liquefied (cryogenic) hydrogen (LH₂) and solid-state hydrogen storage in metal hydrides, such as NaAlH₄, MgH₂, Mg(NH₂)₂+MgH₂+2LiH), chemical hydrides, such as NH₃BH₃, AlH₃ and adsorbents such as AX-21 activated carbon and MOF-5.

- **Safety and risk mitigation measures of hydrogen storage systems and system interfaces for mobile and stationary applications:**

The mobile application includes on-board vehicular storage systems and other advanced portable devices for specialized applications. The stationary systems include hydrogen fueling stations, stationary fuel cells that use hydrogen as the feedstock, auxiliary power systems (APUs), etc. System interfaces include hydrogen dispensing systems and safety hazards arising from accidental fast filling, postulated intrusion of impurities and/or moisture (through hydrogen dispensing devices) during hydrogen charging for vehicular applications, etc.

- **On-board vehicular storage systems materials compatibility issues:**

Examples include hydrogen storage vessels (Type-III and Type-IV vessels), balance of plant (BOP) components (e.g., heat exchanges, pumps, valves, piping), etc. Hydrogen permeation, hydrogen embrittlement, hydrogen attack of Type-III vessel's metal liners and subsequent hydride embrittlement, stress corrosion cracking, liner delamination, thermal fatigue, mechanical fatigue, strain failure of vessel composite materials, low-temperature embrittlement, hydrogen attack of liner materials and blistering phenomenon are also examples of focus areas for this activity.

- **Enabling technologies for fire suppression systems and fire suppression agents compatible with hydride storage material:**

This activity includes fire suppression systems' design, performance and reliability assessment. Chemical characterization and validation tests of fire suppression agents compatible with fires from energetic materials such as metal hydrides and predictive heat transfer models for fire suppression devices dedicated to solid-state hydrogen storage are among the scope of interest under this activity.

- **Safety categorization framework for hydrogen storage materials and associated life cycle impact assessment (LCIA):**

The impact assessment includes potential environmental damage and human health damage resulting from using specific solid-state hydrogen storage materials. The life cycle assessment includes manufacturing, on-board use and end-of-life (EOL) disposal or recycling of the hydrogen storage material.

I. Breakdown of Subtask B by Working Group, Technical Activities and Membership

The following outlines Subtask B working groups, activities and membership.

Activities:

B.1 Working Group - Materials Compatibility Issues

On-board vehicular storage systems materials compatibility issues related to Type-III and Type-IV storage vessels, balance of plant (BOP) components (e.g., heat exchanges, pumps, valves, piping), etc. Hydrogen permeation, hydrogen embrittlement, hydrogen attack of metal liners and subsequent hydride embrittlement, stress corrosion cracking, liner delamination, thermal fatigue, mechanical fatigue, strain failure of vessel composite materials, low-temperature embrittlement, hydrogen attack of liner materials and blistering phenomenon are examples of focus issues for this activity (*Participants: SNL, Powertech, JRC, JARI, UBC, UU (Walter Merrida), Air Liquide*)

B.2 Working Group: Safety of Hydrogen Storage

B.2.1 Safety, reactivity and risk mitigation of hydrogen storage in different forms: compressed hydrogen gas (CH₂), liquefied (cryogenic) hydrogen (LH₂) and solid-state hydrogen storage in metal hydrides, such as NaAlH₄, MgH₂, Mg(NH₂)₂+MgH₂+2LiH), chemical hydrides, such as NH₃BH₃, AlH₃ and adsorbents (such as AX-21 activated carbon and MOF-5).

B.2.2 Risk mitigation tests such as material reactivity tests, mechanical impact sensitivity, dust cloud explosion tests, fire safety and thermal impact sensitivity (storage behavior and thermally-activated pressure relief device (TPRD) design), proto-type tests such as fast depressurization tests, etc.

B.2.3 Mathematical models (e.g., CFD, simulation, etc) for storage vessel stresses, heat transfer during external fire scenarios (localized and engulfing fires), reaction kinetics between the stored hydride material and impurities such as moisture, oxygen intrusion, etc. (*Participants : UTRC, UQTR, SNL, JRC, Air Liquide, GexCon*)

B.3 Working Group - Enabling Technologies for Fire Suppression Devices

B.3.1 On-board fire suppression systems that are compatible with energetic storage materials such as metal and chemical hydrides. (*Participants: NRC-FCIS, JRC, UTRC*)

B.4 Working Group: Life Cycle Impact Assessment (LCIA)

B.4.1 Develop a safety categorization framework for hydrogen storage materials. The driver for safety categorization is material's chemistry. Issues of concern include green chemistry of the material, pyrophoricity, water reactivity, toxicity, potential for runaway chemical reaction, etc.

B.4.2 Life cycle impact assessment (LCIA). The impact assessment includes potential environmental damage and human health damage associated with specific solid-state hydrogen storage materials. Each storage material will be evaluated during its life cycle (cradle-to-cradle) during its manufacturing, on-board use and EOL disposal/recyclability. (*Participants: UTRC*)

B.5 Working Group: Accident Sequence Development and Consequence Quantification

- B.5.1 Use formal probabilistic risk assessment (PRA) tools and methods to develop accident sequences and quantify their consequences. The PRA tools and methods include fault tree analysis (FTA), event tree analysis (ETA) and FT/ET linking methodology.
- B.5.2 Quantify the uncertainties associated with component failure rates and phenomenological events using Monte Carlo simulation to propagate the uncertainties from the accident initiator to the end states in case of ETA or from the basic events level to the top gate in FTA.
- B.5.3 Use qualitative risk analysis (e.g., FMEA) to identify the types of hazards associated with on-board storage system. Depending on the defined system boundary, the risk assessment may also include system interfaces such as hydrogen dispensing systems.
- B.5.4 Use quantitative risk analysis (QRA) to quantify the risks associated with on-board storage system. Depending on the defined system boundary, the risk assessment may also include system interfaces such as hydrogen dispensing systems.

Participants: UTRC, SNL, GexCon

B.6 Deliverables/Products

The anticipated deliverables of Subtask B, as outlined below, aim at improving the current state of knowledge in hydrogen storage materials safety, compatibility and risk management. The theoretical and experimental insights that Subtask B will generate will be useful resource for supporting the risk-informed hydrogen safety regulations and standards.

1. Experimental characterization and risk mitigation insights such as materials reactivity tests and prototypes, solid-state dust cloud explosion tests, sensitivity of energetic hydrogen storage materials to mechanical impact, etc.
2. Predictive theoretical tools such as CFD models, simulations, etc.
3. Probabilistic risk assessment (PRA) framework for accident scenario development using formal PRA tools and methods such as fault tree and event tree analysis.
4. Safety categorization framework for hydrogen storage materials and life cycle impact assessment (LCIA). The impact assessment includes potential environmental damage and human health damage resulting from using specific solid-state hydrogen storage materials.
5. Reports, white papers, conference presentations and publications in scholarly journals.

Subtask C - Early markets: risk identification and hazard analysis (Subtask Leader: Andrei Tchouvelev, AVT)

Commercialization of new hydrogen technologies for mobility, stationary and materials handling applications will result in potential significant involvement of consumers. This dictates to adjust traditional approaches to risk characterization and hazard analysis of industrial hydrogen focused mostly on operator / worker safety to a new reality – widely exposed members of the public. Safety assessment methods, data, and use of prevention and mitigation features need to be tailored to address specifics of early markets which include lack of data and understanding of specific phenomena. Improvement in the data, models, and risk assessment methods are needed in order to generate defensible RCS requirements. This new reality underlines the need to establish systematic data collection from new hydrogen-based

operating facilities (i.e. hydrogen forklift materials handling facilities, car and bus fleets, stationary power units, etc.), specifically failure / leak frequency data. Since new technologies are penetrating densely populated urban environment, special attention should be paid to risk mitigation technologies and methods such as sensors, barriers / walls and safety distances. Last but not least, these findings and methods need to be analyzed and communicated to relevant stakeholders within international codes & standards development activities to ensure those requirements are risk-informed and evidence-based.

Activities

For the work plan period between November 30, 2010 and November 30, 2013, this subtask will focus on five principal activities:

C.1 Failure (frequency) statistics of new hydrogen applications.

The scope will target emerging hydrogen markets. Initially the focus will be on hydrogen forklift operations in US and Canada using a mutually agreed template for data collection consistency. Other available reliable data sources of failure statistics on other applications will not be overlooked. Collected data will then be used in Bayesian statistical analysis to derive credible correlations for the use in quantitative risk assessment. Activity leader: Jeff LaChance, SNL, USA. (*Participants: SNL, NREL, AVT, Powertech, JARI*)

C.2 Improvements in risk assessment and hazard analysis methodologies.

The scope will include monitoring and proposing further developments in risk assessment methodologies. Any related publicly available risk assessment studies and specifically QRAs will be reviewed. Improved methods to address known weaknesses in existing risk assessment activities will be identified. In particular, methods for addressing uncertainty in the data and models will be addressed. Ultimately, it would be desirable to establish an international standard for performing QRAs of hydrogen facilities. Activity leader: Koos Ham, TNO, Netherlands. (*Participants: SNL, UTRC, UNIPI, AVT, GexCon*)

C.3 Systems safety analysis of hydrogen applications.

The scope will include both qualitative and quantitative risk assessments of real world hydrogen systems and equipment with a purpose of establishing their suitability for intended operation (i.e. strengths and weaknesses in design) and identifying potential gaps in existing RCS pertaining to those applications. At this stage, the following applications are being targeted: a) transportation / mobility sector; b) forklifts; c) stationary fuel cell systems; d) renewable energy systems & APUs; e) distribution and refueling infrastructure. Activity leader: Alessia Marangon, UNIPI, Italy. (*Participants: a) JARI, KIT; b) SNL, AVT, UQTR; c) UQTR; d) UTRC, UQTR, CEA; e) SNL, UQTR, AVT, KIT, UNIPI*)

C.4 Prevention and mitigation.

The scope will include evaluation of the following prevention and mitigation measures: a) sensors; b) barriers / walls; c) safety distances based on Subtasks A and B contributions; d) visual inspection, testing and maintenance schedules; e) safety education and training. The evaluation will identify which features are most effective in reducing risk. The cost/benefit of different prevention and mitigation features will also be evaluated. Activity leaders: a) Lois Brett, JRC; b) Bill Houf, SNL, USA; c) Jeff LaChance, SNL, USA, Frederic Barth, Air Liquide, France and Andrei V. Tchouvelev, AVT, Canada; d) and e) Koos Ham TNO.

(Participants: a) JRC, NREL, BAM, NRC-IFCI, UTRC; b) SNL, HSL, Air Liquide; c) SNL, Air Liquide, AVT, UNIPI, TNO; d) Air Liquide; TNO; e) PNNL, NREL, Air Liquide, TNO)

C.5 RCS development support (knowledge analysis and recommendations) to relevant ISO and IEC standard development activities.

The scope will include provision of risk-informed and evidence-based information to and participation in the relevant ISO and IEC technical committees and working groups. It is anticipated that Task experts participating in the work of those committees will provide regular updates on the current status and most critical issues under discussion to the Task membership, and will communicate received feedback to relevant committees. The initial activities will focus on: a) Update of ISO/TC 15916 Basic considerations for safety of hydrogen systems; b) Contribution to ISO 20100 international standard development for hydrogen refueling stations; c) Hazardous areas – link with IEC TC 31. Activity leader: Andrei V. Tchouvelev, AVT, Canada. *(Participants: Air Liquide, SNL, AVT, UQTR, Powertech, GexCon, TNO, UNIPI, CEA, BAM, JRC)*

Subtask D: Knowledge analysis, dissemination and use (Subtask Leader: Steven Weiner, PNNL)

Safety knowledge tools can take many forms and serve to help disseminate the wealth of information that already exists on the safe use and handling of hydrogen and to remove barriers to the successful commercialization of hydrogen and fuel cell technologies. This subtask will enhance databases and websites that have been integral work products and accomplishments of Task 19.¹ New tools and collaborations will be developed to serve worldwide interest in expanded applications of hydrogen and hydrogen systems. This subtask will also take responsibility for working with Subtasks A, B and C to develop the Task 31 Information Plan which serves to capture the work products being developed by this experts working group consistent with the guidelines provided in the IEA Hydrogen Implementing Agreement Handbook.² Subtask D will serve to support work product development in the other subtasks in appropriate ways to ensure that knowledge dissemination for broad use becomes an integral goal of Task 31 as a whole.

Subtask D work scope will include the following collaborations:

D.1 Hydrogen incident reporting, analysis and lessons learned

Two databases play unique and complementary roles in collecting and analyzing hydrogen-related safety event information: (1) Hydrogen Incident Reporting and Lessons Learned Database (“H2incidents.org”) and (2) Hydrogen Incident and Accident Database (HIAD). Collaborations will be developed to capitalize on the unique attributes of these databases for the purposes of ensuring that data, information and knowledge from hydrogen safety events is broadly

¹ Weiner, S.C. and Blake, C.W., “Safety Knowledge Tools Enhanced by International Collaboration,” A White Paper of the International Energy Agency Hydrogen Implementing Agreement Task 19 – Hydrogen Safety, PNNL-19901, October 2010.

² Blum, S.B. and Elam, C.C., “Handbook of Policies and Procedures for the IEA Hydrogen Program,” IEA/H2/PPH-02, August 2002.

disseminated and used to achieve the overall goals of Task 31. *(Participants: PNNL, JRC, IA HySafe, others)*

D.2 Hydrogen Safety Best Practices

“H2bestpractices.org” is a publically available manual and website which is being maintained and enhanced under support of the U.S. Department of Energy. Collaborative opportunities will be sought. *(Participants: PNNL, lead, others)*

D.3 Hydrogen Safety Bibliographic Database

Ongoing literature additions to this database will be encouraged. *(Participants: NREL (lead), all task participants)*

D.4 HyTEX Database

This database was developed under Task 19/Subtask B to facilitate the posting, sharing and use of experimental and hydrogen safety-related data. It contains details of experimental programs that are planned, ongoing and completed. The need to ensure that the database is current and valuable will form the basis for future work. *(Participants: UQTR, (lead, all participants)*

D.5 Training materials for regulators and public safety officials

Individuals and organizations need to assess the safety aspects and certify an increasing number of installations of hydrogen-related technologies in public areas, companies or universities. In Europe, leading players are collaborating to produce and disseminate up-to-date content for hydrogen safety training with the support of the European Commission (HyFacts project). Collaborative opportunities will be sought. *(Participants: Air Liquide, UU, others as appropriate)*

D.6 Risk Communications

The modeling of accidents/incidents including the development and use of visualization tools can play an important role in understanding what happened, preventing/mitigating future occurrences and communicating the risks. Collaborative opportunities will be sought and encouraged. *(Participants: GexCon, others as appropriate)*

4.0 Responsibilities

Responsibilities of the Operating Agent, Task and Subtask Managers, and Activity Leaders are as described in the Annex Plan.

5.0 Schedule For Various Activities and Reports

A Gantt Chart or Time Line for each activity and milestone to be developed by each subtask leader. These documents will be incorporated into the Task 31 Work Plan and approved at the Spring 2011 Experts meeting in Germany.

6.0 Information Plan

As a general policy, it is expected that reports and other information developed under this task will be disseminated as widely as possible, however data generated by specific task activities will be only shared with other participants until approved for public dissemination by the participants of this collaboration.

The Information Plan deals specifically with the information products of the Task. As noted, “careful thought should be given at the beginning of the Task by the participants to the information and products they wish to produce under the Task.”² The Information Plan will be a collaborative effort of Subtasks A, B, C, and D and each major work product will identify the following information, as appropriate:

- Title
- Subtask connection
- Report number (if known)
- Category (to be published or internal working document)
- Purpose of report (or other product)
- Outline of contents
- Intended audience
- Production schedule
- Names and countries of those responsible for writing, editing, production, printing and distribution
- How production and distribution costs will be shared
- Dissemination and publicity plans

7.0 Plans to assess impact of products

The Task intends to conduct seminars and workshops at regular intervals for stakeholders (RCS developers, fire protections authorities, permitting officials, system developers and insurers. The feedback gained will be invaluable in assessing the impact of the work of the Task 31 collaboration.

8.0 Resources requirements

During the development of the Task 31 Work Plan the participating experts have estimated the level of effort of ongoing efforts that will be included in the collaboration to complete work plan.

Country	Subtask Participation				Person Years
	A	B	C	D	Total
Canada	✓	✓	✓	✓	6
EC (JRC)	✓	✓	✓	✓	2
France	✓	✓	✓	✓	7
Greece	✓				1
Germany	✓	✓	✓	✓	10
Italy	✓	✓	✓	✓	2.5
Japan	✓	✓	✓		1
Norway	✓	✓	✓	✓	2
Netherlands	✓	✓	✓	✓	2
UK	✓		✓	✓	2

USA	✓	✓	✓	✓	9
				Total P/Y	44.5

In addition, several other researchers have been identified for participation in Task 31, some of which are members of the Hydrogen Implementing Agreement and others who might join the agreement. These parties are from the following countries: Finland, Denmark, Switzerland, Korea, Brazil, China and India.

The exact amount will be determined by the total participation committed to the collaboration via National Participation Letters.

Appendix 1 – Guide to abbreviation used for participation organizations

Air Liquide	Air Liquide	France
AVT	AVT, Inc	Canada
CEA	le Commissariat à l'énergie atomique	France
Demokritos	National Centre of Scientific Research "DEMOKRITOS"	Greece
GexCon	GexCon AS	Norway
HSL	Health and Safety Laboratory	UK
IA HySafe	International Association of Hydrogen Safety	
JARI	Japan Automotive Research Institute	Japan
JRC	Joint Research Centre - European Commission	EC
KIT	Karlsruher Institut für Technologie	Germany
NRC	Nuclear Regulatory Commission	USA
NREL	National Renewable Energy Laboratory	USA
PNNL	Pacific Northwest National Laboratory	USA
Powertech	PowerTech Labs, Inc.	Canada
SNL	Sandia National Laboratories	USA
Telemark U.	Telemark University	Norway
TNO	TNO	The Netherlands
UBC	University of British Columbia	Canada
UNIPI	University of Pisa	Italy
UQTR	University of Trois Riviere Quebec	Canada
UU	University of Ulster	UK