New Methodology: Hazard Assessment Protocol for Aerospace Hydrogen Systems

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The potentially hazardous environments associated with hydrogen use are controlled through fail-safe system design, operations reflecting best practices, and personnel training that instills a proper regard for safety given the physical, thermo-physical, and chemical properties of hydrogen. Hydrogen is useful in space flight because it is energetic; however, failure to manage it correctly may readily and rapidly produce hazardous conditions. One tool considered in the body of best practice is the use of hazard assessment to review systems and operations. Aerospace hydrogen systems follow hazard assessment practices consistent with standard industry, but must also consider a wide variety of hazards scenarios that arise in unusual or unfamiliar environments.

The NASA White Sands Test Facility developed a new and comprehensive approach to hydrogen hazard assessment. The Hydrogen Hazard Assessment Protocol (HHAP) contains a wealth of information about hydrogen, its qualities and properties, and associated elements for system controls including hardware, intrinsic design, and operational controls. Useful hazards information is provided with procedures to help with hazards considerations. The HHAP addresses hydrogen system design, system and safety engineering, and facility management as practiced in industry – including the aerospace industry – and accords with the requirements and guidelines in the ANSI/AIAA [American National Standards Institute/American Institute of Aeronautics and Astronautics] G-095-2004 *Guide to Safety of Hydrogen and Hydrogen Systems*. Eventually, the procedure will be published through the AIAA and managed as a voluntary consensus document.

HHAP is intended for application to any facility, system, equipment component, or process that involves hydrogen and to the hazards associated with the presence of hydrogen. It is intended to encompass, yet be flexible enough to accommodate, the wide range of applications that can be encountered in hydrogen use: from a large missile launch complex to a small experimental laboratory, and from a large liquid hydrogen production facility to a fuel-cell-powered vehicle in anyone's garage. It can be applied to government as well as to industrial facilities. The HHAP provides a simple procedure for an application that involves minimal hazards, yet is sufficiently complete to provide a critical examination of an application that involves significant hazards. Its purpose remains the same – to protect the workers, the public, equipment, facilities, investments, the mission, and the environment from injury or damage.

The HHAP provides a thorough background of hydrogen physical behavior, hazardous release scenarios, potential hazards without ignition, and combustion hazards. Unique aspects of aerospace hazards assessment are discussed in the HHAP. The assessment approach is adapted to the characteristics of hydrogen and includes the special challenges posed by its behavior. Evaluation for undesired release or entrainment of hydrogen addresses types of releases at ambient and cryogenic temperatures and sub-atmospheric environments, and includes a discussion of confinement geometry. Assessment of combustion considers the effects of flammability, ignition, confinement, and detonation. The HHAP is intended to be an integral tool for risk management.

In any application, hydrogen is controlled within a volume by a combination of elements that includes active engineering control devices, sensors, and passive engineering controls such as inherently safe design or exclusion zones, as well as by operations subject to administrative controls (figure 1). Central to the HHAP analysis approach is the concept that hazards are not intrinsic to hydrogen itself, but arise through the interaction of the elements of control with the hydrogen. Hence, analysis must consider the volume in which the hydrogen is controlled and all elements of control together. This concept is illustrated in the HHAP with diagrams and examples.

We present logically the methodology for hazards assessment protocol; and we provide charts, tables, and forms with useful examples. The HHAP guides the hydrogen user through assessment and documentation of the following major steps:

Identification of volumes for analysis

Assessment of factors/potential causes that might contribute to an unintended release

Evaluation of characteristics of the release within the volume

Determination of potential hydrogen behaviors arising from the release

Evaluation of consequences and associated risks

Recommendations for mitigation

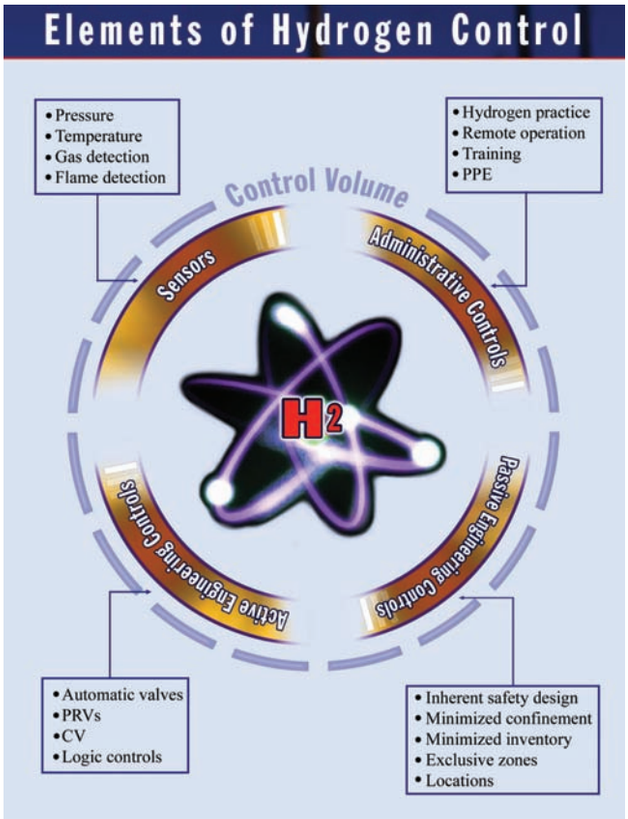

Fig. 1. *Operations subject to administrative controls.*

As an example, the volume analysis flowchart (figure 2) provides an overview of the relationship between analysis of hydrogen volumes and elements, and identification of causes. Analysis findings (Step 3, figure 2) are documented in a Hazard Control Table, an example of which is included in the HHAP. Incremental step-by-step analysis begins with the first volume prioritized for analysis. The first stage (Step 1) of the assessment process entails laying out a strategy for analysis. It is understood that the system may represent a material, a component, a multicomponent device, a facility, or whatever is appropriate for consideration. No one best strategy covers all systems; the HHAP incorporates several strategies in combination. A top-down approach identifies the largest volumes, greatest exposures, or other attributes that point to the worst case; analysis can then bore in to examine smaller volumes that may contribute to the hazard. Alternatively, a bottom-up approach sequentially considers all volumes from the point of hydrogen inventory through the system component by component, then examines volumes adjoining or surrounding the system components until the largest volume or exposure has been considered.

Resource requirements to conduct a hazards analysis using the HHAP depend on system complexity. Current experience suggests that a single component requires 1 day or less, but systems and facilities can take anywhere from 1 week to 1 month, depending on complexity. Complex systems require thorough advance preparation to keep the work group focused and working effectively.

This recommended practice conveys a flexible approach that can be applied to a variety of hydrogen systems at the component level (e.g., valves, instrumentation, connectors, and tanks); system level (e.g., fuel cells, electrolyzers, thrusters, storage systems, and transfer systems); and facility level (e.g., test, storage, and dispensing facilities and remote or auxiliary power systems).

Industry can directly apply the HHAP approach to aid in the development of commercial and transportation hydrogen technologies. Hazards analysis results can be used to help prove code compliance and ensure that liability issues have been addressed. The HHAP may eventually become accepted as state-of-the-art in liability cases. Through management by AIAA, a voluntary standards organization, HHAP may ultimately be used in the evaluation and certification of commercial hydrogen systems.

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The use of this approach to conduct hazard analyses of various hydrogen systems has shown the need for data that are not available, especially combustion and hydrogen embrittlement data. While basic data exist for ambient conditions, more information is needed for hydrogen mixtures at low and elevated pressures. A full evaluation of detonation initiation and some failure modes of electrolyzers requires more information. Finally, basic microgravity combustion data are needed for the aerospace community. When an analysis is challenged by incomplete information, the HHAP provides some examples for strategy to accomplish the hydrogen hazards assessment.

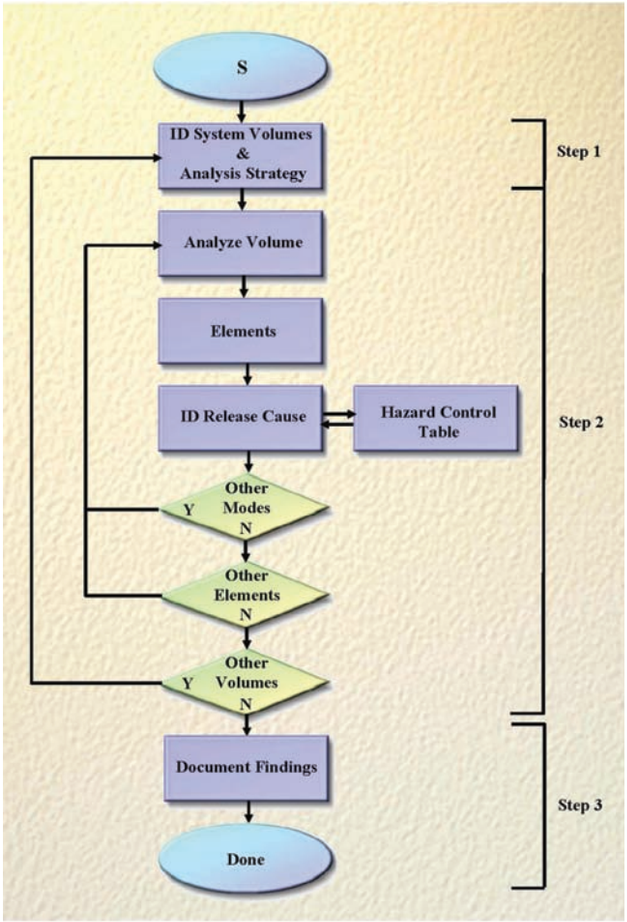

Fig. 2. *Volume analysis flowchart.*

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