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Risk quantification framework of hydride-based hydrogen storage systems for light-duty vehicles

Y.F. Khalil

Physical Sciences Department, United Technologies Research Center, 411 Silver Lane, MS 129-30, East Hartford, CT, 06108, USA

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ABSTRACT

This study aims to develop a quantitative risk assessment (*QRA*) framework for on-board hydrogen storage systems in light-duty fuel cell vehicles, with focus on hazards from potential vehicular collision affecting hydride-based hydrogen storage vessels. Sodium aluminum hydride ($NaAlH_4$) has been selected as a representative reversible hydride for hydrogen storage. Functionality of *QRA* framework is demonstrated by presenting a case study of a postulated vehicle collision (*VC*) involving the onboard hydrogen storage system. An event tree (*ET*) model is developed for *VC* as the accident initiating event. For illustrative purposes, a detailed *FT* model is developed for hydride dust cloud explosion as part of the accident progress. Phenomenologically-driven *ET* branch probabilities are estimated based on an experimental program performed for this purpose. Safety-critical basic events (*BE*) in the *FT* model are determined using conventional risk importance measures. The Latin Hypercube sampling (LHS) technique has been employed to propagate the aleatory (i.e., stochastic) and epistemic (i.e., phenomenological) uncertainties associated with the probabilistic *ET* and *FT* models. Extrapolation of the proposed *QRA* framework and its core risk-informed insights to other candidate on-board reversible and off-board regenerable hydrogen storage systems could provide better understanding of risk consequences and mitigation options associated with employing this hydrogen-based technology in the transportation sector.

1. Introduction

For hydrogen fueled light-duty fuel cell vehicles (*LD-FCV*) to attain a significant market penetration, it is imperative for automotive manufacturers to demonstrate that all potential risks associated with this hydrogen-based technology are well-understood and controlled within acceptable levels. To achieve this goal, *LD-FCV* with on-board solid-state hydrogen storage systems should undergo comprehensive quantitative risk assessment (*QRA*) during their concept development and early design phases. Risk-informed decisions that aim to "*eliminate by design*" all potential safety-critical failure mechanisms can guide design and safe implementation of the on-board hydrogen storage systems in *LD-FCV*.

The objective of this study is twofold: a) propose a *QRA* framework that could be adopted for quantifying the risks associated with on-board reversible and off-board regenerable hydrogen storage systems and b) demonstrate functionality of the proposed *QRA* framework using a case study of a postulated vehicular collision (*VC*). The on-board hydrogen storage medium is assumed to be a reversible complex metal hydride, and sodium aluminum hydride ($NaAlH_4$) has been selected as the candidate reversible hydride in this case study. Again, the focus of this investigation is on the hazards from a potential vehicular collision affecting the on-board hydride-based hydrogen storage vessel. Moreover, hydrogen auto ignition phenomenon is out of scope of the proposed risk quantification framework as the focus is on $NaAlH_4$ related safety events.

The remainder of this paper is organized as follows: Subsection 1.1 presents the elements of *QRA* and subsection 1.2 discusses the fundamental differences between risk-informed (*RI*) and risk-based (*RB*) decision-making processes. Section 2 describes the proposed *QRA* framework for on-board hydrogen storage. Results and discussion are presented in Section 3. Finally, Section 4 summarizes the study's key conclusions and suggested recommendations for future work.

E-mail address: khalilyf@utrc.utc.com.

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Nomenclature

BC	Base case
BE	Basic event
CAFTA	Computer-added fault tree analysis software
CBA	Cost-to-benefit analysis
CNG	Compressed natural gas
CS	Cutset
EPRI	Electric Power Research Institute
ETA	Event tree analysis
FMEA	Failure mode and effects analysis
FTA	Fault tree analysis
F–V	Fussel–Vesely importance measure
GTPROB	Gate probability calculator in *CAFTA*
HAZOP	Hazard and operability analysis
IE	Initiating event
LD-FCV	Light-duty fuel cell vehicle
LHS	Latin Hypercube sampling
MCS	Monte Carlo sampling
MECE	Mutually exclusive and collectively exhaustive
MIE	Minimum ignition energy of the dispersed hydride dust in air
NRC	Nuclear Regulatory Commission
PEM	Proton exchange membrane
PoF	Physics of failure
PRA	Probabilistic risk assessment
PRAQuant	A *CAFTA*-based program to link and evaluate integrated event tree and fault tree models
QLRA	QuaLitative risk assessment
QRA	Quantitative risk assessment
RB	Risk-based decisions
RAW	Risk achievement worth importance measure
RI	Risk-informed decisions
SAPHIRE	Systems analysis programs for hands-on integrated reliability evaluations
UNCERT	a *CAFTA*-based program to perform uncertainty analysis on cutset files using *CAFTA* database

1.1. Elements of quantitative risk assessment (QRA)

A well-structured *QRA* should start by conducting qualitative risk assessment (*QLRA*) such as design failure mode and effects analysis (*d-FMEA*) or hazard and operability (*HAZOP*) analysis.[1] In this study, *d-FMEA* methodology (SAE J1739, 2002; MIL-STD-1629, 1980) is deemed more appropriate since on-board hydrogen storage systems design is still in its conceptual stage. Khalil's application of *d-FMEA* to a conceptual/baseline design of an on-board reversible storage system yielded the following risk information (Khalil, 2011c):

- Identification of critical failure modes and safety hazards, their root causes and their system-level consequences. This information is useful for formulating the dominant accident initiating events (*IE*) and accident progression pathways that can be represented by probabilistic event tree (*ET*) and fault tree (*FT*) models.
- Down-selection of candidate mitigation strategies for the identified risk-significant failure modes and safety hazards. The risk mitigation task typically requires consideration of *risk-to-risk* tradeoffs where designing out a given risk could, unintentionally, introduce one or more new risks that should be addressed. In some cases, the proposed risk mitigation method may involve additional testing or developing physics-of-failure (*PoF*) models to better understand the failure mechanism and how it can be mitigated.
- Quantification of risk reduction (*ΔRisk*) associated with each proposed risk mitigation strategy. This information is useful in evaluating cost effectiveness of each mitigation strategy.

After completing *QLRA*, the remaining *QRA* elements are: a) developing probabilistic event tree (*ET*) model for each accident initiating event and fault tree (*FT*) models for the top events of each *ET* model, b) linking and solving *ET*/*FT* models to quantify the accident sequences, c) quantifying the aleatory and epistemic uncertainties associated with *ET* and *FT* models, d) quantifying the risk importance measures of basic events (*BE*) in the *FT* models, and e) conducting economic consequence analysis for the identified dominant accident initiators. It should be noted that *QLRA*/*d-FMEA* and *QRA* should be treated as living risk models to be periodically updated to reflect the latest relevant state-of-knowledge as it evolves over time (Khalil, 2009).

1.2. Risk-based (RB) versus risk-informed (RI) decisions

When the decision-making process to design out sources of system risks is solely based on insights derived from *QLRA* and *QRA*, the process is referred to as a risk-based (*RB*) decision [5]. The main shortcoming of *RB* decisions is the exclusion of deterministic insights that can be gained from performing engineering calculations and experimental studies. These additional insights could be critical to the decision-making process. To avoid this inherit shortcoming, the present study adopts a risk-informed (*RI*) decision-making process (Khalil, 2000) whereby the *QLRA*- and *QRA*-based insights are blended with insights from physics-based models and experimental observations. As demonstrative examples on the use of the *RI* approach, Khalil conducted dust cloud explosion tests to determine the explosibility of several candidate solid-state hydrogen storage materials including $NaAlH_4$ and performed material reactivity tests (Khalil, 2010a, 2013a, 2013b; Khalil et al., 2013) to determine the degree of pyrophoricity of hydride powder when it comes in contact with water or humid air. As discussed in subsection 3.1, these experimental insights are used for estimating realistic probabilities of occurrence of key phenomenological events that describe progression of accident sequences triggered by postulated initiating events.

2. Quantitative risk assessment (*QRA*) framework for on-board hydrogen storage

Section 2 introduces the proposed *QRA* framework (Fig. 1) and presents a case study to demonstrate its functionality. The case study postulates a collision of a light-duty PEM[2] fuel cell vehicle with an on-board hydrogen storage system that contains sodium

[1] *HAZOP* analysis focuses on identifying deviations of process parameters from desired operating set points.

[2] Proton exchange membrane.