The EU FireComp Project and Risk Assessment of Hydrogen Composite Storage Applications using Bow-tie Analysis

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Hydrogen is expected to become a highly valuable energy carrier and significant mechanism for meeting future energy needs. The 3-year European FireComp project was initiated in 2013 to explore the thermo-mechanical behaviour of high pressure vessels in composite materials when exposed to fire conditions. FireComp brings together European partners from diverse disciplines with the main objective to better characterise the conditions that are needed to avoid loss of hydrogen containment. The project comprises six work packages, which include looking at fire protection strategies and providing input into regulations, codes and standards, as well as dissemination activities. The main activities include:

- Experimental work in order to improve the understanding of heat transfer mechanisms and the loss of strength of composite high-pressure vessels in fire conditions.
- Modelling of the thermo-mechanical behaviour of these vessels.

The current paper briefly outlines the FireComp project, and describes quantitative risk assessments of the hydrogen composite storage systems exposed to fire conditions using bow-tie analysis, based on previous results from earlier tasks. Different applications were considered: stationary applications, transportable cylinders, bundles and tube trailers, and were illustrated by a case study. Risk analyses have been conducted for each application with the aim of leading to the definition of optimised safety strategies; the main goal is to ensure that the composite storage systems are at least as safe as systems using steel cylinders. Further work within the FireComp project will provide bonfire test results to allow refinement of the risk analysis.

Introduction

The current paper briefly outlines the FireComp project, and describes quantitative risk assessments of the hydrogen composite storage systems exposed to fire conditions using bow-tie analysis, based on results from earlier tasks.

The 3-year European FireComp project was initiated in 2013 to explore the thermo-mechanical behaviour of high pressure vessels in composite materials when exposed to fire conditions [FireComp, 2013]. Experimental work has been carried out to improve the understanding of heat transfer mechanisms, thermal degradation, combustion and the loss of strength of composite high-pressure vessels in fire conditions. The modelling of the thermo-mechanical behaviour of these vessels was also set-up and validated against full-scale fire tests. The FireComp project brings together partners from diverse expertise: a Gaseous Compressed Hydrogen (GCH) technology integrator as a coordinator (AIR LIQUIDE), a pressure vessel supplier (HEXAGON), a leading player in international Standards, Codes and Regulations development (UK Health & Safety Executive (HSE)), experts in industrial risks (INERIS), experts in thermal radiation and mechanical behaviour of the composite (CNRS (Pprime & LEMTA), LMS Samtech), experts in thermal degradation and combustion of composites, numerical simulation (Edinburgh University and LMS Samtech) and an expert in European Research & Development collaborative project management (ALMA). The project comprises six work packages, namely:

- WP 1 Project management;
- WP 2 Fire protection strategy;
- WP 3 Thermal properties of composite material exposed to fire;
- WP 4 Mechanical properties of composite material exposed to fire;
- WP 5 Testing composite reservoir behaviour in reference fires and model validation;
- WP 6 Input into Regulations, Codes and Standards and dissemination.

The ultimate aim of the work described in this paper, that is risk assessment using bow-tie analysis, was to formulate fire protection safety guidelines (in terms of risk reduction measures for hydrogen (H_2) composite cylinders) and potentially make recommendations for input into regulations, codes and standards.

Context

This paper summarises the work conducted within one of the FireComp tasks under Work Package 2: Fire Protection Strategy. It presents a quantitative risk assessment of the hydrogen storage systems that use composite technology, being exposed to fire conditions. The systems to be studied were identified, followed by a preliminary risk analysis and identification of relevant fire scenarios. This paper describes the work done using the results of the preliminary risk analysis to conduct a detailed risk analysis, using bow-tie diagrams. As this paper was written whilst the project was still ongoing, some parts of the analysis are still evolving, and thus this paper simply presents a snapshot analysis, i.e. an example study.

A number of hydrogen storage applications were considered, such as a bundle in transportation, or a cylinder in a forklift. For each application, several bow-tie diagrams were drawn (49 in total, for all applications considered), capturing all known information on the potential thermal aggressors of the storage, and safety barriers used to reduce the risk of a hydrogen leak or burst. Each bow-tie has been quantified, using input data from AIR LIQUIDE (fire scenario frequencies), HSE (probability of failure on demand, PFD, of thermal pressure relief devices, TPRDs) and INERIS (passive safety barriers). Subsequently, within each application, the frequencies of occurrence of a leak and burst were calculated by adding the contribution of each bow-tie. A case study for a 280 kW/m² fire partially impacting a forklift, will be presented in this paper.

When this paper was written, there were some outstanding bonfire tests which were still being carried out by INERIS within Work Package 5. The results of these were to be used to:

- inform the hypotheses regarding the expected behaviour of composite cylinders exposed to a fire;
- better understand the behaviour of the cylinders when exposed to fire (hence useful for model calibration); and
- obtain parameters for proper dimensioning of TPRD (time before burst and rupture pressure / internal pressure evolution with time).

The frequencies of a cylinder leak and burst was also assessed for classic technology, and compared to the values computed for composite technology, in order to help define safety objectives that should be implemented.

FireComp Bow-tie diagrams

The bow-tie diagram is a combination of a fault tree on its left-hand side and an event tree on its right-hand side. The link between the two trees is usually called the "top event". The primary causes identified in the fault tree (leftmost events) are referred to as "initiating events" (threats). The event tree starts from the top event and leads to "consequences", which usually are events we want to reduce risks of, either in probability or in severity.

In this paper, we identify three consequences of composite cylinders exposed to a fire:

- No effect / leak through the body of the cylinder: when the hydrogen storage is exposed to a sufficiently aggressive fire impact, the fusion of the liner can occur[1]. This phenomenon can create a leak where the storage is supposed to remain airtight, or avoid a burst by allowing a pressure drop through that leak. A leak through the body of the cylinder would feed the surrounding fire without causing more significant effects;
- Leak through TPRD: this means the hydrogen storage leaks through the well-functioning TPRD as a result of a thermal impact;
- Burst: this means the hydrogen storage bursts as a result of a thermal impact and a failure to open, of the TPRD[2].

Figure 1 illustrates how a bow-tie is organized, constructed and used. This is a four-step method, colour coded as red, yellow, green and blue on the figure.

The four steps are applied as detailed below:

- 1st Step (Red): Identify the top events.

The quantification is concerned with assessing the frequency of a dangerous consequence (leak or burst) of the hydrogen storage when exposed to a thermal impact. The top events must then be a given thermal impact followed by a storage failure. In this regard, the initiating events associated are the fires producing this level of impact on the hydrogen storage.

[1] The phenomenon of leak throughout the body of type IV cylinders has been reported by Bustamante-Valencia (2015). Leaks through type IV liners were observed when the cylinder was initially pressurized at "low" levels compared to working pressure. It is produced by the fusion of polymeric liner and the consequent loss of tightness. The degradation of the liner often occurs before the cylinder burst. This effect cannot occur on type III cylinders whose liner is metallic.

[2] In theory, a cylinder could burst even if the TPRD opens. In fact, in order to prevent the burst from happening, we must ensure the TPRD enables the pressure inside the hydrogen storage to drop faster than the decrease of the rupture pressure due to the degradation of the envelope. In this paper, and by extension in the whole project, we assume the TPRD to have been properly dimensioned.

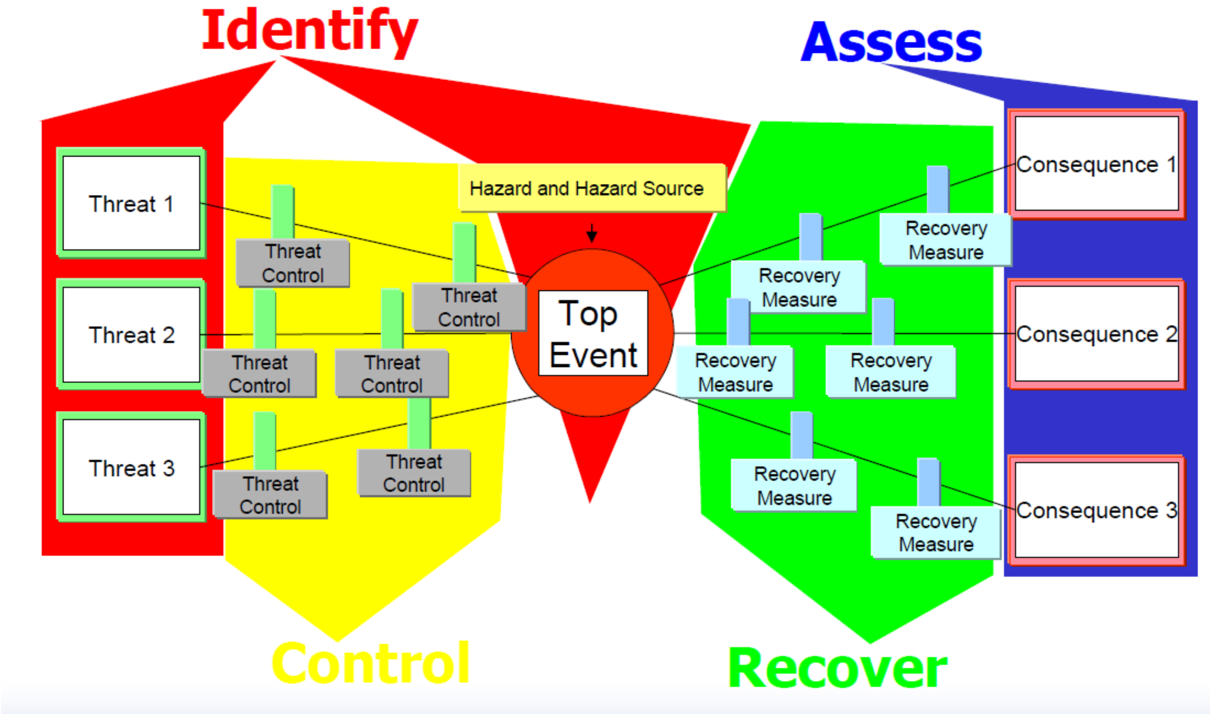

Figure 1: Bow-tie diagram (Risktec, 2007)

- 2nd Step (yellow): List, and position on the fault tree, the safety barriers selected to be involved in reducing the probability of occurrence of the top event.

These barriers will prevent one or more initiating events from having an impact on the storage. This means we do not analyse when the barriers behave properly, since nothing will happen if they do (i.e. we assume a safety barrier is efficient and has been correctly selected). We only assess the cases when they fail to respond on demand, by taking into account their PFD (Probability of Failure on Demand) during the quantification.

- 3rd Step (green): List, and position on the event tree, all the relevant risk mitigation measures; this includes measures reducing the probability of one or more consequences, as well as measures reducing the intensity of the consequences (for example a firewall).

In this work, we do not take into account the latter, since the consequence/ impact of a hydrogen leak or burst is out of the scope of the FireComp project. We simply assess the frequency of occurrence of any leak or burst, whatever the leak flow rate or volume.

- 4th Step (blue): Assess the consequences using all the information displayed on the bow-tie diagram.

Review of the preliminary risk analysis

The first step was to conduct a review of the preliminary risk analysis performed within the FireComp project, to give the elements required for the first step of the construction of bow-ties. The scope of the study needed to be defined first (application and environment), since bow-ties will vary depending on the use of the storage. These need to be paired with the list of initiating events that can have a thermal impact on the storage, and regrouped accordingly.

Applications involving high pressure hydrogen storage

Hydrogen cylinders are not usually used as a single element but integrated in bundles or other type of frames. Ten combinations of an application and an environment needed to be studied, as presented in table 1. For clarity, each combination of an application and an environment will be referred to as an application. For example, an AIR LIQUIDE (AL) bundle used in transportation is an application; the same bundle used in a customer facility is another application.

Table 1: AIR LIQUIDE (AL) and HEXAGON (HEX) applications involving high pressure hydrogen (H_2) storage with its environment

Application categories	Application	Environment	N°
Trailers	AL Tube trailers type III	On the road	**A1**
		In a plant	**A2**
	HEX type IV trailers	On the road	**A3**
		In a plant	**A4**
Bundles	AL bundles	In transportation	**A5**
		In customer facility (on the ground)	**A6**
	HEX bundles	In transportation	**A7**
		In customer facility (on the ground)	**A8**
Refuelling stations	Refuelling stations (H_2 source)	In a plant away from the vehicle	**A9**
Vehicles	Forklifts	In a plant	**A10**

List of initiating events

Thirteen initiating events (I1-I13) that may have a thermal impact on the hydrogen storage in at least one of its applications were selected. It is important to note that malicious acts of arson are not taken into account in this risk assessment: they are out of the scope of these kinds of assessments since they are impossible to quantify and pertain to a very different field of expertise.

A preliminary risk analysis was carried out by AIR LIQUIDE and HEXAGON to check whether the initiating events were physically possible or not, for each application. Following review by FireComp Partners, some events were discounted for some applications because they were considered too improbable.

gives the updated list of events which was selected for the quantitative risk assessment. “Yes” in the table means that the scenario is physically possible, “No” means that the scenario is physically impossible or has been considered too improbable in the preliminary risk analysis held by AIR LIQUIDE (AL) and HEXAGON (HEX) prior to this study.

N°	Initiating event, Ii	Is the initiating event selected for this application?									
		AL Tube trailers type III – on the road	AL Tube trailers type III – in a plant	HEX type IV trailers – on the road	HEX type IV trailers – in a plant	AL bundles – in transportation	AL bundles – in customer facility	HEX bundles – in transportation	HEX bundles – in customer facility	Refuelling station (H_2 source)	Forklift
	Road accident involving a trailer or a car or forklift during transport										
I1	Fire of the tyres	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**Yes**
I2	Oil or fuel fire (the source of fuel is the one of the truck)	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**	**No**	**No**
I3	Fire propagation from another car or another truck on the other side of the truck, or at a fuel station	**Yes**	**No**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**Yes**	**No**	**No**
I4	Fire after Roll-over	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**No**	**Yes**
I5	Compartment fire (engine or interior parts)	**No**	**No**	**Yes**	**Yes**	**No**	**No**	**Yes**	**No**	**No**	**No**
I6	Battery fire (hybrid and fuel cell vehicles)	**No**	**No**	**Yes**	**Yes**	**No**	**No**	**Yes**	**No**	**No**	**No**
	Hydrogen (H_2) flame impact										
I7	From TPRD of another bundle or cylinder (normal opening or not) of hydrogen storage	**No**	**No**	**No**	**No**	**No**	**Yes**	**Yes**	**Yes**	**No**	**No**
I8	From (HP) fittings, valves or piping connections	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
	Fire on a plant (customer plant or filling plant)										
I9	Pallets fire	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**Yes**	**Yes**
I10	Electric fire	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
I11	Building (combustible walls) fire	**No**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**	**Yes**	**Yes**	**Yes**
I12	Fire while filling H_2/ tow-away	**No**	**No**	**Yes**	**Yes**	**No**	**Yes**	**Yes**	**Yes**	**No**	**Yes**
	Forest fire										
I13	Forest fire	**No**	**No**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**No**

Table 2: Initiating events and applications

Identification of the top events

In order to create relevant fault trees and event trees, we chose, for the top events, all the possible "impact" the hydrogen storage can receive. We define the "impact" as a combination of the heat flux received by the storage and the surface of the storage impacted by the fire.

Table 3 details the results of the quantification of the impact, based on elements provided by INERIS.

N°	Initiating event	Fuel/material involved	Quantification of the impact	
			Heat flux (kW/m^2)	Surface involved (qualitative)
	Road accident involving a trailer or a car or forklift during transport			
1	Fire of the tyres	Mix (elastomer, carbon black, steel)	45	Partial
2	Oil or fuel fire (the source of fuel is the one of the truck)	Oil, fuel (gasoil)	125	Partial
3	Fire propagation from another car or another truck on the other side of the truck, or at a fuel station	All	125	Partial
4	Fire after Roll-over	All	280	Engulfment
5	Compartment fire (engine or interior parts)	Mix (elastomer, seats, *etc.*)	45	Engulfment
6	Battery fire (hybrid and fuel cell vehicles)	Mix (elastomer, battery fluid, *etc.*)	45	Engulfment
	Hydrogen (H_2) flame impact			
7	From TPRD of another bundle or cylinder (normal opening or not) or hydrogen storage	H_2	280	Local
8	From (HP) fittings, valves or piping connections	H_2	280	Partial
	Fire on a plant (customer plant or filling plant)			
9	Pallets fire	Wood	45	Engulfment
10	Electric fire	Wire	45	Partial
11	Building (combustible walls) fire	Various	125	Engulfment
12	Fire while filling H_2/ tow-away	H_2	280	Partial
	Forest fire			
13	Forest fire	Wood	45	Partial

Table 3: Synthesis of impact characterisation

Based on Table 3, we can identify 7 types of impacts, meaning there are 7 different top events. The list of these top events and the initiating events leading to those is provided in Table 4.

N°	Top event	N°	Initiating event
T1	45 kW/m^2 partial	1	Fire of the tyres
		10	Electric fire
		13	Forest fire
T2	45 kW/m^2 engulfment	5	Compartment fire (engine or interior parts)
		6	Battery fire (hybrid and fuel cell vehicles)
		9	Pallets fire
T3	125 kW/m^2 partial	2	Oil or fuel fire (the source of fuel is the one of the truck)
		3	Fire propagation from another car or another truck on the other side of the truck, or at a fuel station
T4	125 kW/m^2 engulfment	11	Building (combustible walls) fire
T5	280 kW/m^2 local	7	From TPRD of another bundle or cylinder (normal opening or not) or hydrogen storage
T6	280 kW/m^2 partial	8	From (HP) fittings, valves or piping connections
		12	Fire while filling H_2/ tow-away
T7	280 kW/m^2 engulfment	4	Fire after Roll-over

Table 4: List of the top events

Note: *initiating event n°11, building fire, has a special treatment in some of the bow-ties. In fact, when a safety barrier is positioned on a fault tree between an initiating event and a top event, it means this safety barrier is supposed to eliminate completely the impact if it functions properly, and the impact remains unchanged when the barrier is faulty. When this fault tree is quantified, the frequency of occurrence of the initiating event will be multiplied by the probability of failure on demand of the safety barrier to assess the frequency of the top event. However, one of the safety barriers associated with initiating event n°11 is a safety distance ranging from 3 meters to 15 meters. Even if this safety distance is successfully enforced, the impact received by the hydrogen storage does not disappear; it drops from a 125 engulfment (T4) to a 45 partial (T1). The bow-ties constructed will separate initiating event n°11 into 2 sub-events: one with the safety distance enforced, leading to top event T1, and another with the safety distance not enforced, leading to top event T4 and with a frequency of occurrence adjusted to take into account the probability of non-enforcement of the safety distance.*

Review of the safety barriers

We needed to position the selected safety barriers involved in reducing the frequency of occurrence of the top events in order to finalize the fault trees. This had to be carried out for each bow-tie. The easiest way to do it was to proceed application by application: for each of them, we started from the list of the selected initiating events from

. Then, for each initiating event, the safety barriers identified previously were reviewed and selected only if they help reduce the frequency of occurrence of the related top event.

It is important to note that some barriers have not been taken into account, even if they obviously have a positive impact on reducing the frequency of occurrence of the top event. One example is the bundle fastenings for type III trailers, to prevent fire after roll-over. The safety barrier is efficient and helps to reduce the frequency of that initiating event. However, the fastenings are always installed on type III trailers. Since the frequency of this initiating event is assessed by using an accident database, the safety barrier is already taken into account in the frequency. Hence, it will not be positioned again on the fault tree to avoid double-counting.

Hypotheses on the expected hydrogen storage behaviour when the TPRD fails to open

As mentioned before, when the hydrogen storage is exposed to a sufficient impact, the fusion of the liner can occur and add a random factor to the behavior of that storage. This phenomenon can create a leak where the storage is supposed to remain airtight, or avoid a burst by allowing a pressure drop through that leak. However, the study of the leak by fusion of the liner is not one of the objectives of the FireComp project, and since it is not a very well known and assessed phenomenon yet, it will not be explicitly studied in detail here.

With that in mind, it is assumed that a hydrogen leak leading to significant effects can only happen through a TPRD opening. We then made the assumption that a hydrogen storage when the TPRD fails to open can either be damaged, but not enough to burst (we will call this scenario "no effect", associated with the "leak through body"), or burst when exposed to a thermal impact. The assumptions are detailed in Table 5.

Table 5: List of assumptions for the expected storage behaviour when TPRD fails to open

N°	Top event	Consequence
T1	45 kW/m^2 partial	No effect / Leak through body
T2	45 kW/m^2 engulfment	No effect / Leak through body
T3	125 kW/m^2 partial	No effect / Leak through body
T4	125 kW/m^2 engulfment	Burst
T5	280 kW/m^2 local	Burst
T6	280 kW/m^2 partial	Burst
T7	280 kW/m^2 engulfment	Burst

Hypotheses on the expected TPRD behaviour

Finally, we needed to know how the TPRDs are expected to behave when exposed to each of the top events identified. TPRDs are initiated by fusion of a component which is expected to be very reliable provided the component reaches the fusion temperature. Therefore, it appears that even the lowest impact is able to activate a TPRD if it behaves properly (this is considered later). The thermal relief temperatures of the most usual TPRD range from 85°C to 110°C.

Concerning the TPRD behaviour, two sets of hypotheses can be distinguished, whether the TPRD is efficient i.e. it detects the fire and opens, or not:

- the TPRD is 100% efficient, whatever the type of fire: the TPRD activates when exposed to any of the 7 top events identified in Table 4, including partial fires (for some cases, this means that several TPRD have been placed on the storage);
- the TPRD is partially efficient, according to the type of fire:
  - for an engulfment fire, the TPRD is 100% efficient;
  - for a local fire, the TPRD is inefficient;
  - for a partial fire, the efficiency of the TPRD depends on the application: the bigger the hydrogen storage, the less efficient the TPRD (the risk not to detect the fire if there is only 1 TPRD on the storage is higher).

Depending on the set of hypotheses, the frequencies of leak and burst may vary significantly. This will be relevant in one of the final outcomes of the project: the safety recommendations. If the second set of hypotheses leads to unacceptable frequencies, one of the recommendations could be to increase the number of TPRDs to increase the efficiency to 100%.

Moreover, the unexpected opening of a TPRD will not be taken into account for the quantification of the leak and burst of the hydrogen storage, since it cannot happen under these hypotheses. However, the failure of a TPRD to open is studied, and leads to the consequences identified, depending on the top event.

Another aspect to consider is the dimensioning of the TPRD. In order to prevent the burst from happening, we must ensure the TPRD enables the pressure inside the hydrogen storage to drop faster than the decrease of the rupture pressure due to the degradation of the envelope. Proper dimensioning of the TPRD is out of the scope of the FireComp project and hence the starting hypothesis. The results from other work packages may change this hypothesis at the completion of the FireComp project.

Construction of the bow-ties

By putting together all the information, we were able to draw the bow-ties for each application. For clarity, the bow-tie representing top event *y* for application *x* is called bow-tie A*x*.T*y*. The red-cross symbol in the bow-tie diagrams denotes when it is deemed not possible for a top event to escalate into that particular consequence. For the purpose of illustration, only the bow-tie diagrams for application A10 are presented here.

A10: Forklifts

5 bow-ties exist for this application, for top events T1, T2, T4, T6 and T7.

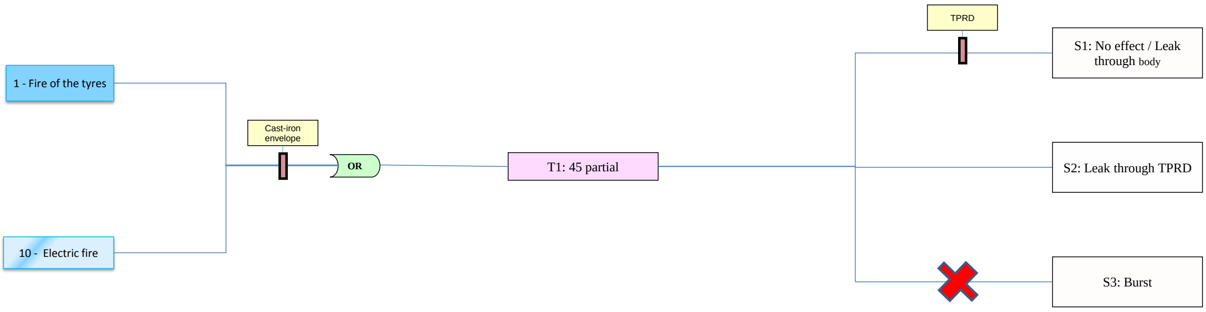

Figure 2: Bow-tie A10.T1

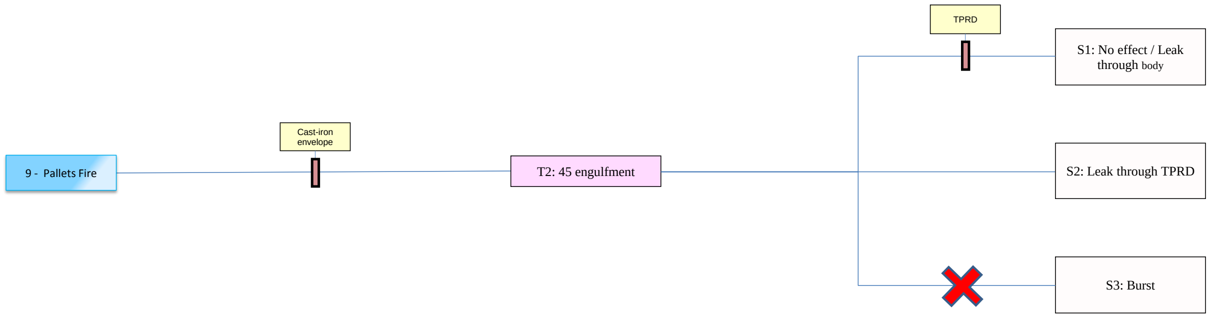

Figure 3: Bow-Tie A10.T2

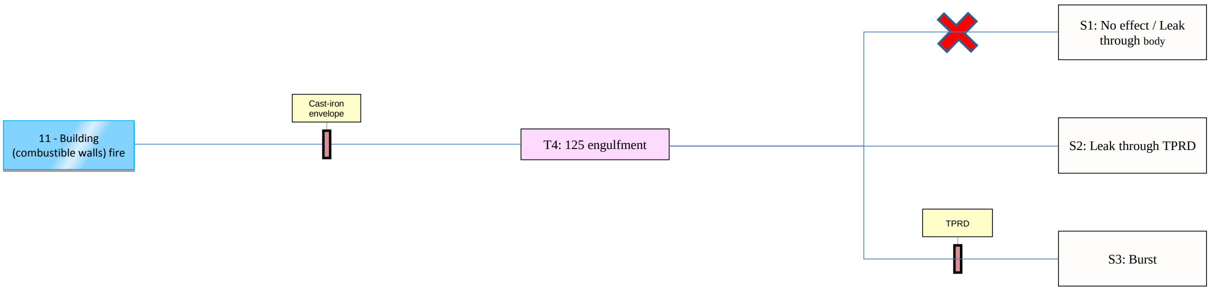

Figure 4: Bow-tie A10.T4

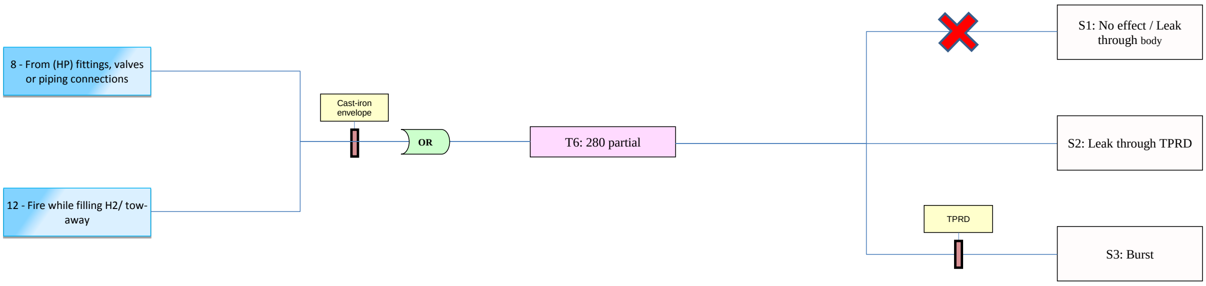

Figure 5: Bow-tie A10.T6

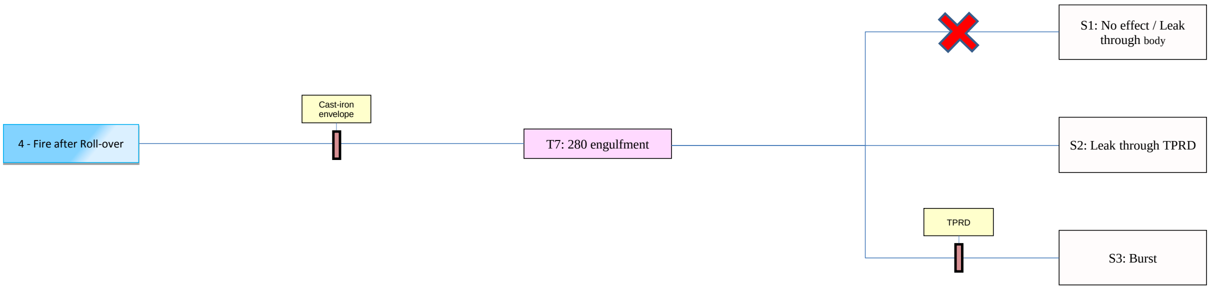

Figure 6: Bow-tie A10.T7

Bow-tie quantification

In order to assess the frequencies of leak and burst for each bow-tie, the frequencies of each top event for each application were first assessed. Then, depending on the expected behaviour of the storage when the TPRD fails to open, the frequency of a leak and a burst was calculated by multiplying the probability of failure on demand of a TPRD when relevant.

To assess the probabilities of occurrence of each top event, the following data were needed:

- The frequencies of occurrence of all the 13 initiating events for each application (an initiating event may have different frequencies depending on the application);
- The probabilities of failure on demand (PFD) of all the safety barriers positioned before a top event.

Most of these data were provided by AIR LIQUIDE. The remaining data, the probabilities of failure on demand of some safety barriers, were assessed by INERIS based on reference guides [INERIS, 2008]. These probabilities are very conservative and broadly rounded up in order to be as sure as possible the frequencies of major accidents are not underestimated, since the bow-tie model does not facilitate taking uncertainties into account and since there is no real way to quantify those uncertainties.

Finally, the probability of failure on demand of the TPRDs was not straightforward to quantify. It was not possible to find failure frequencies for a TPRD, the nearest available being the probability of a failure to open on demand for a conventional pressure safety valve (PSV) from the OREDA Offshore Database [OREDA, 2009]. The safety function we want to assess is the opening of a thermally-activated PRD in a degraded state (meaning exposed to a fire), but no such value exists in either public or AIR LIQUIDE internal database.

Thermally-activated Pressure Relief Devices are a technology completely different from pressure-activated rupture discs or safety valves. Based on their knowledge of TPRDs and pressure safety discs, AIR LIQUIDE believes the probability of failure to open on demand of a TPRD when exposed to a fire is lower than the probability of failure on the same demand of a disc.

Moreover, failure rates (λ) characterise all the failures modes of a device: for a TPRD, failure to open in case of fire *and* unintended opening without fire. This last failure mode is out of the scope of the FireComp project, and not part of the QRA calculations presented here.

To determine the probability of failure to open of a TPRD for a vessel exposed to fire, the following points had to be considered:

- values for pressure-activated PRDs (bursting discs, safety valves...) are not relevant;
- probability of failure to open in fire of a thermally-activated PRD (excluding unintended openings) is unknown;
- values for thermally-activated PRDs exist in neither public nor AIR LIQUIDE internal database;
- like other types of PRDs, TPRDs are devices that rely on a physical phenomenon of its materials to open in case of fire. Hence a very low probability of not opening when exposed to fires.

Based on those considerations, we used the following values:

- **For an engulfing fire:** public database NPRD (Reliability Analysis Center, 1991) gives a value of $\lambda = 1.38\times10^{-6}$ per hour for the failure of rupture disc PRDs. For the reasons above, this value is over-conservative. We used it to calculate the PFD of a TPRD, in the absence of better data. For the calculation of the PFD, a proof test interval of 1 year will be taken as a common basis.
- **For a partial fire:** With the first set of hypotheses presented earlier, the TPRD has the same PFD as in an engulfing fire. With the second set, this paper considers, for illustrative purposes, that the TPRD is 50% efficient for vehicles, and 33% efficient for trailers and bundles.
- **For a local fire:** With the first set of hypotheses presented earlier, the TPRD has the same PFD as in an engulfing fire. With the second set, its PFD is 1 since it is deemed inefficient.

When the TPRD is 100% efficient, the probability of failure to open in fire is 6.04×10^{-3} (called PFD_{avg}). If it is only partially efficient (i.e. it is exposed to the fire and then opens in a proportion of the cases, x), the equivalent PFD equals $xPFD_{avg}+(1-x)$. It will be multiplied by the frequency of the top events to assess the relevant scenarios, as illustrated by the Case Study below.

- The frequency after an "OR" gate is the sum of the frequencies of the initiating events; this supposes the initiating events are all mathematically independent; meaning the occurrence of one does not give any information on the occurrence of another one.
- The frequency after a safety barrier is the product of the frequency before the barrier, and the probability of failure on demand of the barrier. For event trees, the frequency on the other branch (when the barrier behaves properly) is equal to the product of the frequency of the top event by 1 minus the probability of failure on demand of the barrier.

Finally, the frequencies of leak and burst were summed within each application to get a single value for each application. For example, for application 10, the frequency of a burst is the sum of the frequencies of a burst obtained from Bow-tie A10.T4, Bow-tie A10.T6 and Bow-tie A10.T7. The calculated values were compared with the values for competitive technology from generic databases. It was assumed that the risk associated with competitive technology is broadly acceptable; if the value for high pressure technology is lower, it will be considered acceptable, if the value is higher, it will be considered unacceptable and safety objectives will be defined to reduce the values to an acceptable threshold. This was to ensure that composite technology does not introduce a higher level of risk than the competitive technology already in place.

Case study

The following case study looks at a 280 kW/m² fire partially impacting a forklift. It is associated with bow-tie A10.T6:

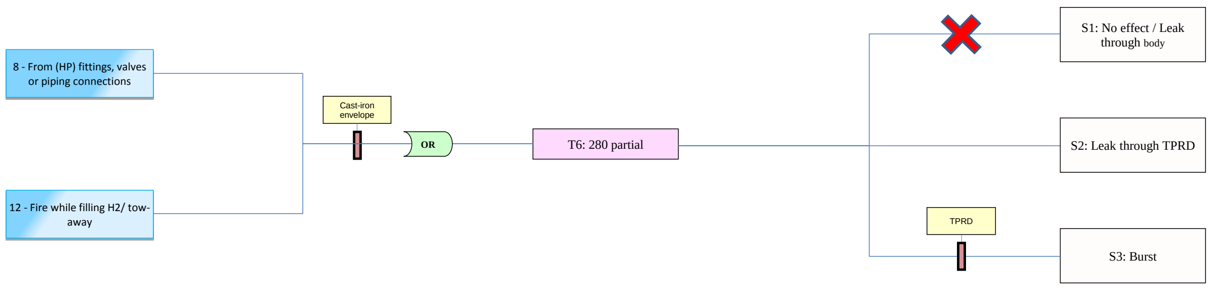

Figure 7 Bow-tie A10.T6

Table 4 identifies 2 initiating events corresponding to top event T6: I8 and I12.

confirms these 2 initiating events are physically possible for application A10. The cast-iron envelope is positioned as a safety barrier in the fault tree. As per Table 5, we assume that top event T6 is severe enough to allow a storage burst if there is no TPRD, or if it fails to open. As such, the TPRD failure leads to scenario S3: burst, and its proper functioning leads to scenario S2: Leak through TPRD. The values necessary to quantify this bow-tie are:

- the frequency of initiating event 8 (I8): fire from (HP) fittings, valves or piping connections;
- the frequency of initiating event 12 (I12): fire while filling H_2 / tow-away;
- the probability of failure on demand (PFD) of the cast-iron envelope;
- the probability of failure on demand (PFD) of the TPRD.

The frequencies of the two initiating events are provided by AIR LIQUIDE, based on their own return of experience on these events. The values that were provided to INERIS are 10^{-3}/y for the fire from (HP) fittings, valves or piping connections, and 10^{-6}/y for the fire while filling hydrogen / tow-away.

The PFD of the cast-iron envelope was assessed based on the Omega 10 method (INERIS, 2008). The envelope is a passive barrier. However, the cast-iron envelope was not designed to protect the hydrogen storage from an incoming fire: it serves as a counterweight. Nonetheless, its efficiency to protect the storage from a thermal impact has been asserted by AIR LIQUIDE. As such, INERIS proposes a corrected PFD of 10^{-1} for the cast-iron envelope, instead of 10^{-2}. Finally, the PFD of the TPRD is 6.04×10^{-3} with the first set of hypotheses and $6.69\text{x}10^{-1}$ with the second set of hypotheses, as previously explained. The results of the quantification of bow-tie A10.T6 are presented in Table 6.

Table 6 Quantification of bow-tie A10.T6

	I8	I12	Cast-iron envelope	TPRD	T6	S2: Leak through TPRD	S3: Burst
Formula	$f(I8)$	$f(I12)$	PFD_{CE}	PFD_{TPRD}	$f(T1) = [f(I8)+f(I12)] \times PFD_{CE}$	$f(S2) = f(T1) \times (1-PFD_{TPRD})$	$f(S3) = f(T1) \times PFD_{TPRD}$
Value	10^{-3} $/y$	10^{-6} $/y$	0.1	6.04×10^{-3} (100% efficient) $6.69\text{x}10^{-1}$ (33% efficient)	1.00×10^{-4}	9.94×10^{-5} $4.97\text{x}10^{-5}$	6.04×10^{-7} $5.04\text{x}10^{-5}$

Conclusions

A methodology to quantitatively assess the risk of hydrogen composite storage systems exposed to fire conditions has been described in this paper. During the preliminary risk analysis phase, a number of hydrogen storage applications were identified and linked to several initiating events, fire scenarios and safety barriers used to reduce the risk of hydrogen leak or burst. This led to the construction of a number of bow-tie diagrams that enable the determination, within each application, of the frequencies of occurrence of a leak and burst using input data from AIR LIQUIDE, HSE and INERIS. The paper illustrates the quantification process through a case study.

Results drawn from the quantitative bow-tie risk assessment will be used to compare between composite and conventional storage, hydrogen leak and burst frequencies when exposed to fire. This will lead to the issuing of recommendations and safety guidelines for input into regulations, codes and standards, about composite hydrogen storage technology, which aims to be at least as safe as existing conventional technology. It is expected that further work will be needed, e.g. to determine the appropriate number and location of TPRDs, but these are not within the scope of the FireComp project.

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