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Safety approach for composite pressure vessels for road transport of hydrogen. Part 1: Acceptable probability of failure and hydrogen mass

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ABSTRACT

Hydrogen is a promising alternative for current energy carriers. Compressed gas cylinders are the storage systems closest to the commercialization of hydrogen in vehicles. The safety factors in current standards are seen as restrictive for further growth and competitiveness of hydrogen infrastructure. A probabilistic approach can be employed in order to give a rational background to the safety factors. However, an acceptable probability of failure needs to be estimated before calculating the safety factors. The discussion of determining the acceptable probability must include the mass of hydrogen since this determines the consequences of an accident. It is concluded that an annual probability of failure of 10^{-7} would be appropriate for small pressure vessels containing a few kilograms of hydrogen. Larger pressure vessels of a few hundred kilograms or more should be designed for an annual probability 10^{-8}.

Introduction

Hydrogen is a promising alternative or substitute to existing fuels. In order to make hydrogen a viable alternative, infrastructure has to be built for producing, distributing and storing the gas. One important aspect in building the supply network is transporting gaseous hydrogen on the road. Today, hydrogen is transported mainly for industrial customers in steel pressure vessels on truck trailers. Some composite pressure vessels also exist. However, much larger capacity will be needed when hydrogen filling stations for cars and busses become widespread. Using composite pressure vessels instead of steel pressure vessels would increase payload and reduce the cost of transport. These features can be very lucrative for industrial gas companies [1].

Composite pressure vessels for hydrogen transport are already built today. They are built according to ISO standards ISO 11119-3 [2] and ISO 11515 [3]. Similar pressure vessels are also built for transporting Compressed Natural Gas (CNG). The experience of operating trucks with composite pressure vessels has been good and no major disasters have happened. However, the current ISO standards are seen by many as restrictive for further growth and competitiveness of hydrogen infrastructure. There is ongoing discussion about the reduction of safety factors for the pressure vessels. One problem is that current standards do not give an explicit or scientific reasoning for the existing safety factors. The

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applicability of lower safety factors to larger vessel sizes and higher pressures is therefore difficult to evaluate. A different framework is needed to base decisions on.

Composite pressure vessel approval can also be carried out according to the principles of structural reliability [4]. The first step in this approach is establishing an annual probability of failure which can be viewed as acceptable for this structure. Experience from similar applications, which are already in widespread use, can be used as helpful guidance. Once the probability of failure is decided, safety factors can be calculated for all design/failure criteria. Currently existing standards, which at least partially use the probabilistic approach range from composite components to structural engineering [5–7].

The aim of this paper is to find an acceptable probability of failure for composite pressure vessels for road transport of hydrogen. A starting point can be a comparison with other existing structures; e.g. an excellent overview is given in Ref. [8]. A wide range of acceptable failure probabilities can be found in literature for different industries and applications, such as aerospace, marine, or civil engineering structures [6–11], usually ranging from 10^{-4} to 10^{-6} $year^{-1}$. The current study also argues that an acceptable probability of failure needs to agree with the maximum consequence of the accident.

Overview of concepts

It is very important to be specific about the scope of the analysis otherwise a great deal of confusion can be created. It is therefore emphasized that only one component of the whole system (i.e. the pressure vessel) is looked at in this paper. The whole system i.e. the whole fleet of trucks in traffic, with piping, valves etc. connected to each pressure vessel is out of the scope of this paper. The pressure vessel is expected to be designed and manufactured according to relevant standards and good practices. It is also assumed that the loads will not be higher than the vessel is designed for. However, even under these conditions it will have a probability of failure higher than zero. As a matter of fact, the failure probability can never be zero. Although this probability is very small, it is one crucial component in determining the safety factor and there lies the main interest of current work.

For an overview of concepts influencing this decision problem, one can start with very general principles as shown in Fig. 1.

The probability of failure of a hydrogen pressure vessel will not be affected by the amount of hydrogen stored inside the container. The probability of failure is achieved by design, manufacturing and the safety factors. Large vessels can have lower probability of failure than smaller ones or vice versa if they are designed and manufactured accordingly.

However, the consequence of a severe accident does increase with hydrogen mass. In this paper only the highest consequence events are reviewed. This is because the failure of the whole pressure vessel is simply the highest consequence event there is. All of the hydrogen gets almost instantly released due to a physical burst and it ignites and explodes in the worst case. The larger the amount of released hydrogen, the more travelers on the road and bystanders will be affected by the released energy.

Therefore, the maximum amount of transportable hydrogen will be limited by what the society is willing to accept as the maximum consequence of an accident. Accident consequences and their frequencies must be accepted by the society as the actual risk carrier. Societal risk criterions have been developed which help to determine if the risk is still acceptable to the society.

Small accidents will inevitably occur (where the whole vessel will not fail), e.g. pipe or valve failure, with a small number of injuries or fatalities, just as with other currently used fuels. These small accidents will be more frequent, but they are out of the scope of this work as they are not related to the failure of the whole pressure vessel.

In the following sections a detailed look is given to further clarify the aforementioned concepts and to calculate approximate numerical estimations.

A truck trailer traveling on the road may transport several pressure vessels. The volume or mass transported is seen here as the amount stored in one single pressure vessel. It is assumed that in an accident scenario only one of the several pressure vessels will burst or release H_2. The other pressure vessels may burst or leak due to the failure of the first vessel, creating a domino effect. However, the consequences of the subsequent sequential explosions will typically be less severe, because they will mainly affect already damaged areas. This means the amount of H_2 causing damage is limited to the amount in one pressure vessel. It also implies that the pressure vessels are not connected by piping or are separated from each other by closed valves. If there are pressure vessels of different sizes on the same trailer, a conservative approach would be to consider the biggest one for determining the overall consequences.

Historical evidence

An essential part of learning about safety is the study of case histories. It gives indications about influential factors determining the accident consequences and also the sheer physical scale of such accidents. The safety records of hydrogen transport are good and no large scale disasters have happened in recent years. A brief overview of four catastrophic accidents related to the transport of other hazardous materials serves as a grim demonstration of what can go wrong.

Case studies from open literature

San Carlos De La Rapita Disaster

According to [12], in July 11, 1978, a 19 t road tanker carrying propylene in Tarragona, Spain caught on fire, eventually leading to an explosion. The tanker was severely overfilled and actually weighed out at 23.5 t. It had no pressure relief valve. The accident happened next to a fully booked camp site, where some 800 people were staying. The driver had a recommended route but actually took an alternative road which went past the camp. As a result 217 people lost their lives and approximately 600 were injured. The tanker vehicle was torn