HYDROGEN REFUELLING STATIONS FOR PUBLIC SECTOR QUALITY AND SAFETY IN THE USER INTERFACE

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ABSTRACT

Hydrogen stations and supply systems for public transport have been demonstrated in a number of European cities during the last four years. The first refuelling facility was put into operation in Reykjavik in April 2003. Experience from the four years of operation shows that safety related incidents are more frequent in the user interface than in the other parts of the hydrogen refuelling station (HRS). This might be expected, taking into account the fact that the refuelling is manually operated, and that, according to industrial statistics, human failures normally stand for more than 80% of all safety related incidents. On the other hand the HRS experience needs special attention since the refuelling at the existing stations is carried out by well trained personnel, and that procedures and systems are followed closely. So far the quality and safety approach to hydrogen refuelling stations has been based on industrial experience. This paper addresses the challenge related to the development of safe, robust and easy to operate refuelling systems. Such systems require well adapted components and system solutions, as well as user procedures. The challenge to adapt the industrial based quality and safety philosophy and methodologies to new hydrogen applications and customers in the public sector is addressed. Risk based safety management and risk acceptance criteria relevant to users and third party are discussed in this context. Human factors and the use of incident reporting as a tool for continuous improvement are also addressed. The paper is based on internal development programmes for hydrogen refuelling stations in Hydro and on participation in international EU and IPHE projects such as CUTE, HyFLEET:CUTE, HySafe, and HyApproval.

1.0 INTRODUCTION

Hydrogen stations and supply systems for public transport have been demonstrated world wide during the last few years. By the end of 2006 some 160 hydrogen refuelling stations (HRS) were built globally. A major part of these are demonstration stations including extensive R&D activities. Even though most stations contain the same equipment modules, the station design is not harmonized. One reason may be the fact that different industrial companies have been involved in establishing the initial stations, combining their industrial experience with local requirements. Most of the demonstration stations are located at industrial areas and bus depots with a few and dedicated users and a limited range of vehicles. There seems, however, to be a trend towards more public stations with design more comparable to conventional fuel stations for petrol and diesel.

The CUTE and HyFLEET:CUTE partnership represents one of the major demonstration programmes on hydrogen refuelling and hydrogen vehicle technology. Experience from the four years of operation of demonstration projects shows that safety related incidents are more frequent at the vehicle/HRS user interface than in the other parts of the HRS, even though the refuelling has been carried out by well trained and dedicated personnel following procedures and systems closely. In most cases only a few operators have been appointed for this task. Further development of the refuelling equipment and systems needs special attention, and the experience from the demonstration projects should be closely analysed.

2.0 THE USER INTERFACE

The user interface is where the refuelling is done, comprising of an access road, a designated area for the vehicle and the dispenser unit with the integrated communication unit, e.g. a monitor and keypad, and the connection point at the vehicle.

Handling of the dispenser and refuelling system requires a number of operations that have to be done in a certain order. In the CUTE and HyFLEET:CUTE projects an earthing cable and a communication cable between the dispenser and the vehicle were part of the system.

Figure 1: Bus refuelling in Madrid (left) and car refuelling in Berlin (right) (Photo: Hydro)

Hydrogen refuelling stations can be split in two main categories, stations for public refuelling and stations for fleet vehicles refuelling. Today the user interface at a public HRS is expected to be similar to the user interface at refuelling stations for diesel and petrol. HRS for buses and other fleet vehicles are expected to be located at areas with access control and trained personnel, e.g. at bus company depots. The user interface at stations for fleet vehicles will most likely have a more complex design than those for public use.

3.0 SAFETY ASPECTS AT THE USER INTERFACE

Like petrol, natural gas and other vehicle fuels, hydrogen is a reactive substance that must be handled with respect. The main safety aspects at the user interface are related to the risk associated with a potential ignition of a hydrogen leakage at the station or at the vehicle. However, user-friendly design and clear refuelling procedures are also vital to ensure a safe user interface.

The station needs safe, robust and reliable refuelling equipment and systems that are applicable to hydrogen, well fit for vehicles and that are easy to operate. Hydrogen leakages should be prevented, and, even more important, ignition of flammable mixtures of hydrogen in air must be avoided. Leakages may be caused by inadequate components or equipment, malfunction of equipment, or human errors. Any hydrogen leakage should be allowed to disperse quickly and dilute out of the flammability range. Ignition sources must be under control.

4.0 QUALITY AND SAFETY APPROACH IN DESIGN OF HYDROGEN STATIONS

4.1 Industrial approach

The fact that most of the hydrogen stations in operation today are based on industrial experience also means that the quality and safety approach has been based on industrial experience. In CUTE and HyFLEET:CUTE risk assessments, evaluating risk according to acceptance criteria that are commonly used by the oil and energy industry, have been carried out. However, previous experience with the use of hydrogen for vehicle transport is limited, and adapting industrial experience in the public sector is challenging.

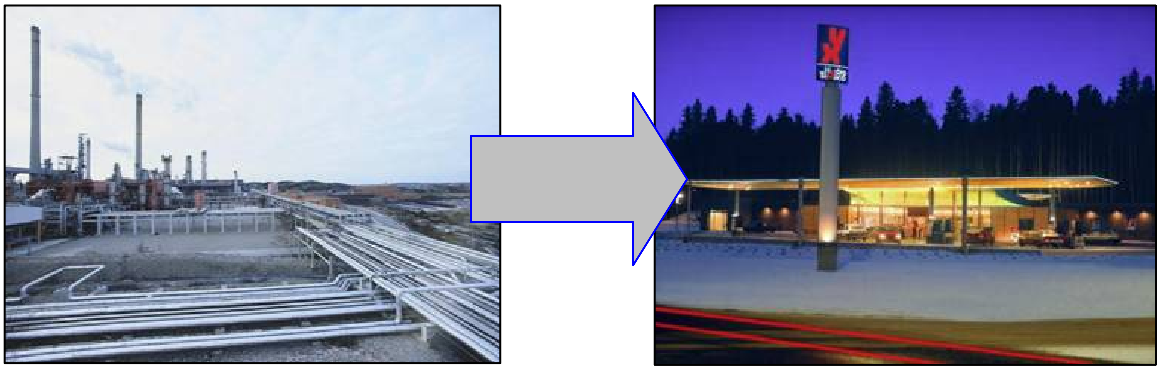

Figure 2: Transferring experience from the industrial arena to the public arena (Source: Hydro)

Methane/compressed natural gas (CNG) and liquefied petroleum gas (LPG) have been used for vehicle fuel for a number of years. Nevertheless, petrol and diesel are still the most commonly used fuels for transport purposes. The limited experience with hydrogen for this purpose has motivated the use of CNG experience in the design of HRS. Components primarily developed for CNG are used for hydrogen applications.

When using the CNG experience for hydrogen applications, it must be recognized that hydrogen is different from methane, with different chemical and physical properties relevant to the safety aspects. For instance, compared to methane hydrogen has a wide range of flammable concentrations in air and a very low ignition energy. These differences which are illustrated in figure 3 should be acknowledged and taken into account in design of the hydrogen refuelling station and in layout and operation at the user interface.

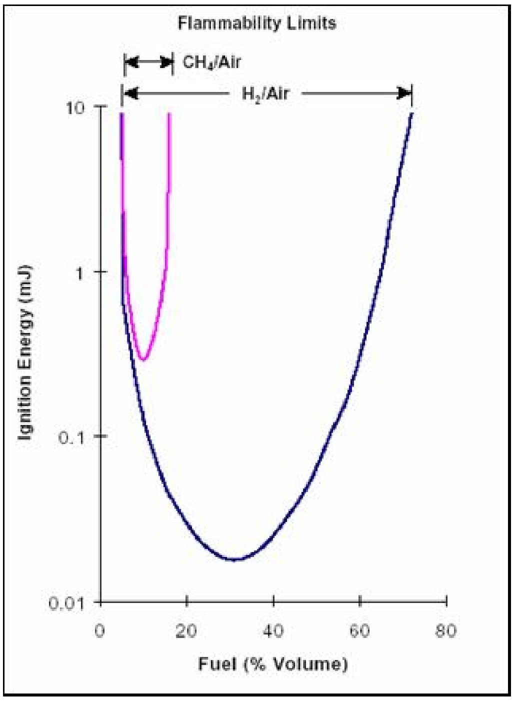

Figure 3: Ignition energy of hydrogen and methane vs. concentration in air [1]

In the process industry risk assessments are commonly used in design and implementation of new processes and new technologies. Transfer of the hydrogen from the industrial sector to hydrogen refuelling stations and private cars on the public sector also needs to deal with the challenge to adapt the industrial based quality and safety philosophy and methodologies to new hydrogen applications and customers.

4.2 Hydrogen refuelling station technology

Current "state of the art" technology and systems for hydrogen refuelling stations are mainly based on components and systems optimized for industrial use. Hence, the current HRS established within the demonstration projects are assembled more or less like an industrial pilot plant using components that are commercially available, but not necessarily originally developed for hydrogen applications.

At the current demonstration projects hydrogen is either trucked in, supplied by pipeline from an external source or produced on-site by water electrolysis or reforming of hydrocarbons. In addition to the hydrogen supply units, a typical HRS also comprises units for hydrogen compression, storage, and dispensing as well as utility systems.

Hydrogen has significant lower volumetric energy density than other conventional fuels like petrol, diesel and natural gas. Based on lower heating value, the energy content of 1 Nm3 of hydrogen is equivalent to 0.34 l of petrol [2]. Given the low density of hydrogen, gaseous hydrogen is compressed to high pressures in order to have hydrogen available for refuelling at any time. The footprint of a HRS is small and the dimensions of pipelines, components and equipment at the HRS are much smaller than at an ordinary industrial plant. The small scale components and systems combined with high pressures represent challenges to manufactures of components and systems designed for hydrogen.

Compared to other refuelling stations, the hydrogen refuelling stations are much more complex than refuelling stations for conventional fuels like petrol and diesel. This complexity may also give rise to an increased risk compared to refuelling stations for conventional fuel.

Ideally, risks associated with the hydrogen systems upstream the dispenser should not affect the public user of the station. Neither should the public user of the HRS pose any risk to the hydrogen systems upstream the dispenser. Design and layout of the HRS user interface should be based upon these assumptions.

Industrial experience with hydrogen dispenser units is scarce, and most units implemented at the current HRS are based on CNG experience. A variety of dispenser solutions are being used. A common characteristic of the bus dispensers is that they are more complex than ordinary petrol dispensers. Hydrogen dispensers for public use, e.g. in Berlin, tend to look like those in use at petrol stations. To ensure safety at the HRS user interface, the hydrogen dispenser including the refuelling hose and nozzle, should be based on hydrogen specific technology. Development of hydrogen dispensers is ongoing.

4.3 Risk Assessments as Design and Engineering Support

Within the process industry a common industrial safety culture has been developed during the last 2 – 3 decades. This safety culture emphasizes inherent safety, risk based safety management and continuous improvement based on lessons learnt from quality and safety monitoring. In CUTE and HyFLEET:CUTE industrial partners were involved in establishing the stations, and an industrial based quality and safety philosophy was used in design of the stations. Risk assessments as illustrated in figure 4 were carried out. It should be noticed, however, that the risk acceptance criteria used were normally technical criteria related to process industry. Specific criteria must be developed to support safe and user friendly operation at the HRS.

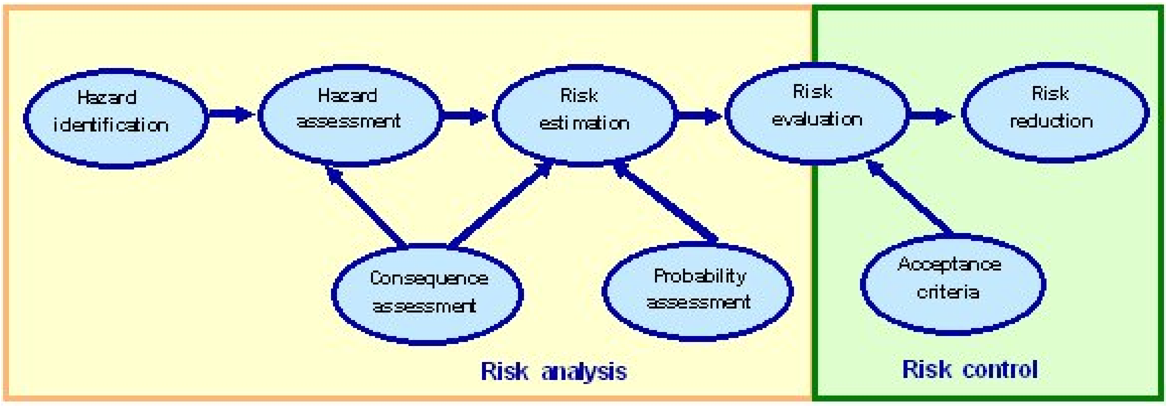

Figure 4: Risk Based Safety Management (Source: Hydro)

The HyFLEET:CUTE partnership has established zero accidents as one of the project targets. Even though incidents have occurred within the project, the target is met. However, the timeframe of the project is limited, and the experience database is limited. In lack of factual data and experience, generic data collected from other applications should be used in risk assessments of new HRS, but all hydrogen specific properties which may affect components and materials in use must be taken into account. Both technical factors and human factors should be addressed in the risk assessment.

In order to develop inherently safe hydrogen refuelling stations and user interfaces, hydrogen-specific know-how must be recognized and made available for standardization efforts. At this stage the experiences should be compiled as "Current Best Practice" in order to allow for further and continuous improvement of systems and components based on the experience gained from operation of the current demonstration stations.

5.0 THE USER INTERFACE AND RISK ASSESSMENT METHODOLOGIES

Various methodologies may be used to assess risk at the hydrogen station user interface. Methodologies commonly used in design and engineering are illustrated in figure 6.

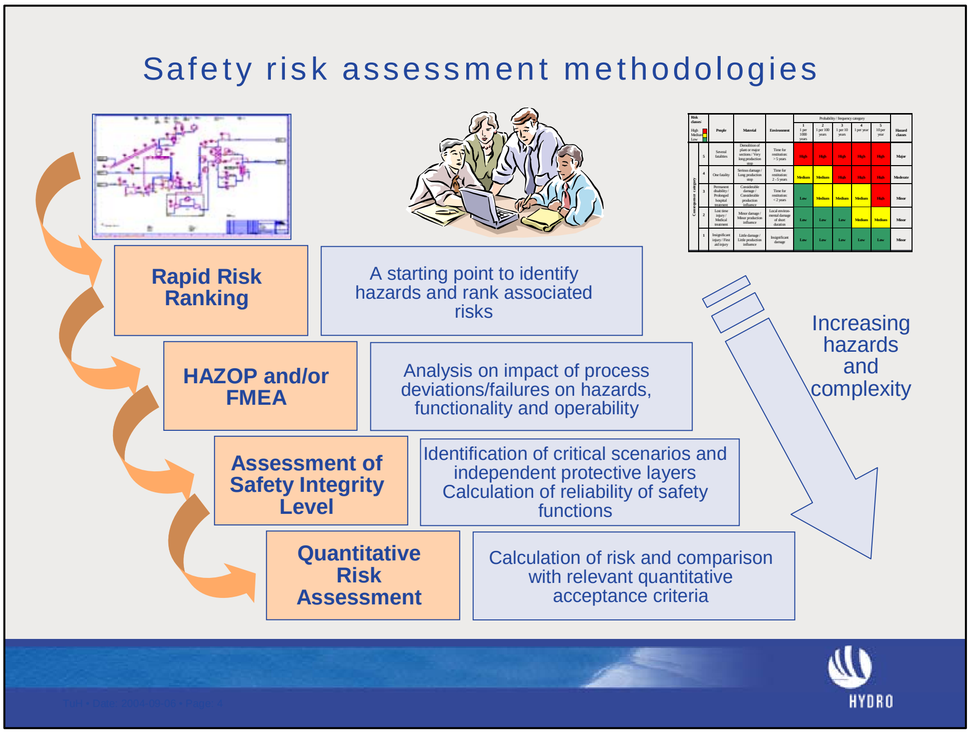

Figure 5: Safety Risk Assessment Methodologies. (Source: Hydro)

HAZOP (HAZard and OPerability) study is probably the method most commonly used for safety assessment in the process industry. All HRS included in the CUTE project were subject to HAZOP studies [3]. At the user interface, functionality and safety of the dispenser and the refuelling equipment is crucial. Design of dispensers and refuelling equipment and systems would benefit from a FMEA (Failure Mode and Effect Analysis).

HRS located in urban areas or in locations where any accident may cause major consequences, the risk associated should be quantified through a QRA (Quantitative Risk Assessment). The safety systems involved, and in particular the instrumented safety systems, e.g. gas detection and automated shut down systems, should be scrutinized through a SIL (Safety Integrity Level) assessment or a LOPA (Layer of Protection Analysis), unless the station is designed, built and installed on other risk-informed basis.

However, risk assessment of the user interface must include evaluation of the users' actions and behaviour during the refuelling operation. Job Safety Analysis and Work Processes Analysis are risk analysis methodologies suitable for this purpose.

6.0 THE USER INTERFACE AND THE HUMAN FACTOR

6.1 The Users' Expectations

The initial expectations to the refuelling station and the fuelling process in CUTE and HyFLEET:CUTE were rather high taking into account the major companies participating in the infrastructure part of the project (e.g. Shell, BP, Air Liquide, HEW). A survey carried out among the cities involved in CUTE and HyFLEET:CUTE illustrated that the failures and down–time experienced were disappointing for the bus companies. Problems related to the filling procedure have caused both downtime and lack of confidence in the hydrogen refuelling systems. HRS reliability, trouble shouting and problem solving was ranked very poor by most cities. Improvement have been acknowledged, however, e.g. for solving problems with the refuelling nozzle in 2004 and 2005.

The user of the refuelling equipment is currently a trained person that is part of a demonstration project. Often this is an employee in one of the companies in the partnership, e.g. a bus company representative, a car company employee or a representative for the infrastructure company. Even though these users do not represent the average users in the future hydrogen station, their expectations and experiences are crucial for development of a high quality and safe user interface.

Based on the knowledge from the projects and the experiences gained during the operation so far, users' expectations of hydrogen dispensing are similar to dispensing of conventional fuels. The refuelling systems should be easily accessible, understandable, easy to use, and well fit to the connection to the vehicle. The number of operations included in refuelling should be as few as possible and the time used for the fuelling process should be as short as possible.

6.2 The Human Factor in Design of the User Interface

Dispensing of gaseous hydrogen is done automatically when the nozzle is coupled to the vehicle receptacle. The gas temperature is increased when the gas expands inside a vehicle tank, and to avoid overheating of the vehicle tank, the filling rate must be carefully controlled. This affects the refuelling time which so far has proven to be far more extensive than for conventional fuels. Fast filling of hydrogen is done with filling time ranging from 12 minutes for large vehicles to 2 - 3 minutes for smaller vehicles. The manual operation is limited to connecting and disconnecting the nozzle to/from the vehicle. No manual operation is needed during the refuelling itself.

Given the difference in fuel properties and refuelling time it is not obvious that hydrogen should be refuelled in the same way as petrol. Neither is it obvious that hydrogen dispensers and refuelling equipment should look like petrol dispensers and petrol refuelling equipment.

There are currently different practices of design and use of the HRS, and there are different approached to procedures for the use of hydrogen dispensers. At some stations the vehicle and the dispenser are connected without hydrogen in the system; the refuelling is activated with a remote start button. At other stations the refuelling is done with people close to the refuelling point. In the CEP Berlin project the filling of the cars is done manually – similar to petrol.

Acknowledging that the human nature involves a range of potential failures related to e.g. sense impressions, memory, mental conditions, decision-taking, way of acting, the human factors should be considered in design and layout of the user interface. Operators/users should be involved in design of the user interface.

7.0 CONTINUOUS IMPROVEMENT OF THE USER INTERFACE

7.1 Quality and Safety Monitoring

The experiences from the demonstration projects have revealed that components and systems at the user interface are still not optimized. Some deviations and deficiencies have had the potential to affect safety in a way that might give rise to unsafe operation. By including quality and safety management as an integral part of daily operation, any deviation, deficiency or safety related incident is followed closely. In such cases all deviations that occur at the station are recorded, discussed and followed-up to improve components, equipment or systems.

The quality and safety monitoring in the CUTE and HyFLEET:CUTE projects has been done by data-collection based on a set of 12 indicators [3].

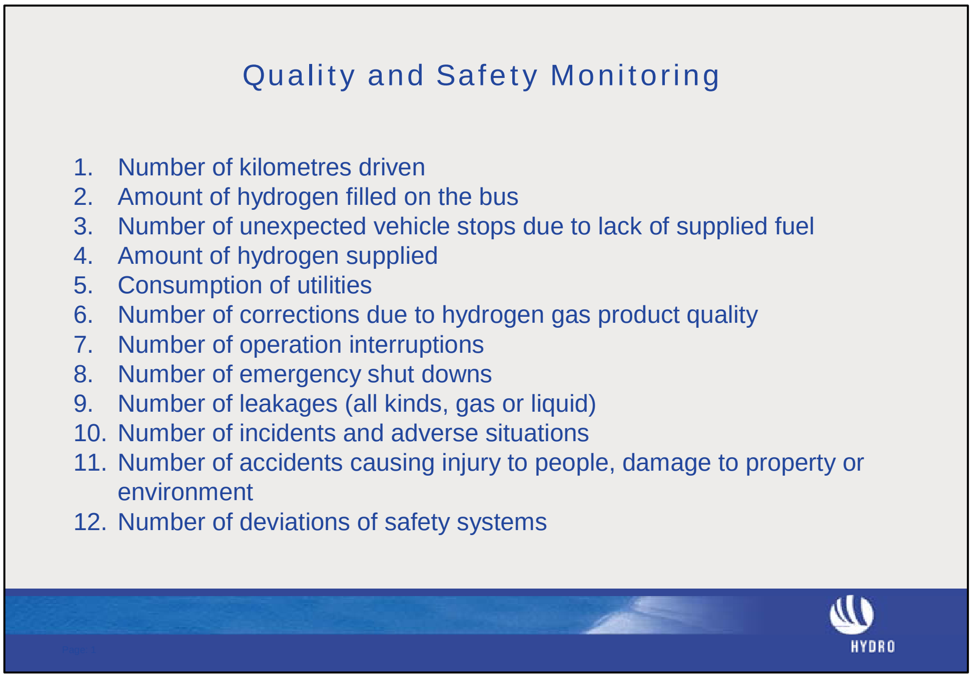

Figure 6: Quality and Safety indicators developed for the CUTE project [3]

The data collection has been done by each local project and in a web-based system for data submission. In addition to this an Incident Reporting System was launched in June 2004, due to several minor safety related incidents. The Incident Reporting System has been used for reporting if safety and security incidents in the several demonstration projects. The reporting form has been increasingly used during the projects, and improvements have been made based on these reports.

In the CUTE project some 65 incidents were reported in detail using the reporting form during the two years of operation. As illustrated in figure 7, about 1/3 of the incident reports were related to the user interface [4].

Including the first year of operation in the HyFLEET:CUTE project, nearly 100 incidents have been reported in this reporting regime all together. Nearly 40 of the reports are related to the user interface.

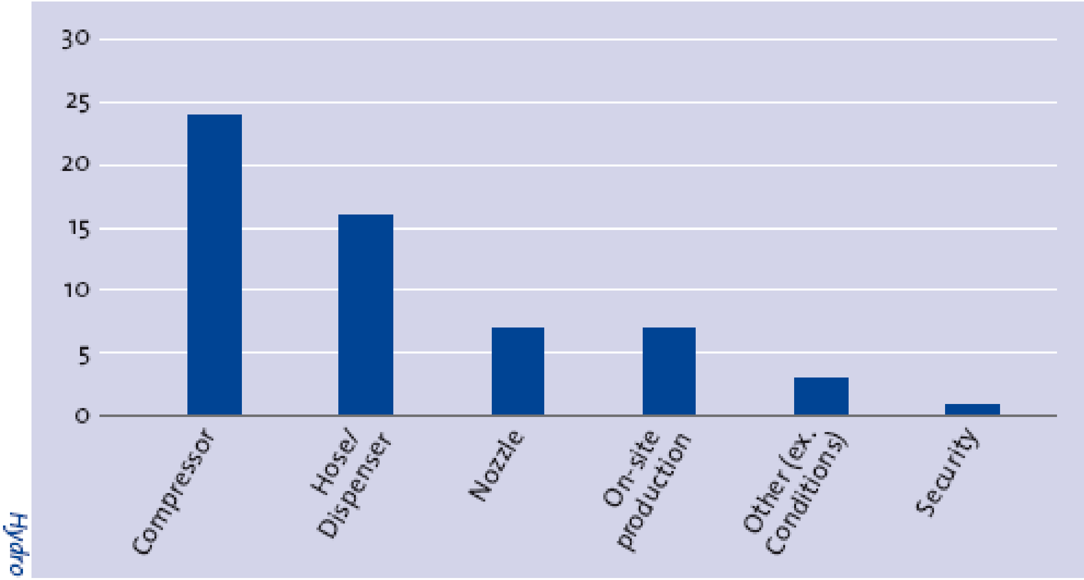

Figure 7: Incidents reported in detail in the CUTE project 2004 – 2005 [4].

Failures and deviations related to the nozzles, hoses, breakaway couplings as well as handling and access to operation have been frequently reported. Improvements have been made, but there are still unsolved issues related to e.g. fuelling hoses. It should also be noticed that most of the reports have been related to technical issues. Human errors are hardly reported. There might be several reasons for that. One being a possible mismatch between the functionality of the refuelling equipment and the user's expectations; another might be lack of knowledge and lack of compliance with instructions. Another reason might be inadequate design motivating the user to improvise.

The experiences from CUTE and HyFLEET:CUTE illustrate an immature technology for the user interface and that improvements are needed. In order to establish viable solutions, not only further development of components and equipment is required. All incidents, deviations and deficiencies detected during operation and inspection should be scrutinized with respect to root causes. Operators should be included in investigation, analyses and follow-up in order to develop user friendly solutions.

A systematic approach to continuous improvement by using the PDCA (Plan-Do-Check-Act)-methodology (figure 8) has been used in CUTE and HyFLEET:CUTE and has proven most effective.

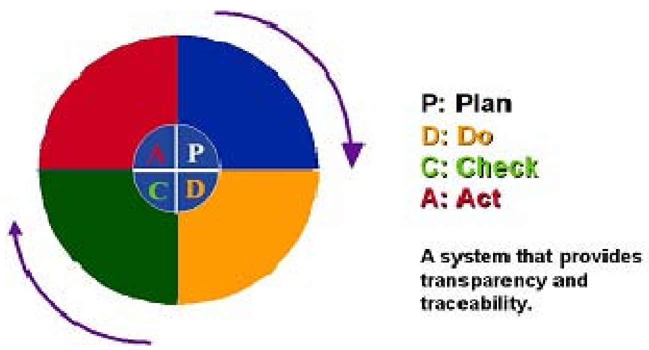

Figure 8: The PDCA-methodology for continuous improvement [3]

7.2 Challenging components, systems and instructions

As mentioned above, a major part of the failures and deviations reported during the CUTE and HyFLEET:CUTE operation was related to the user interface. Also compressors turned out to be a challenging component, but the deviations reported do not necessarily indicate that the compressor technology is immature. The operational conditions in the HRS with variable loads, start and stops and higher pressure demands are different from that you normally find in the industrial sector. Compressors fit to the operation at the hydrogen station need to be developed.

In the user interface several components can be identified as challenging. The refuelling nozzles as well as the refuelling hoses are critical components. The nozzles have been subject to modification initiated by the CUTE experiences. The hoses are still challenging and leakages have been experienced also in the HyFLEET:CUTE project. Lack of information and manufacturer involvement has resulted in a situation where the pathway to a high quality system is difficult to see.

Hydrogen refuelling stations for public use are expected to be based on self service refuelling and remote control. Equipment and systems for petrol and diesel dispensing have been developed for decades; equipments and systems for hydrogen dispensing are still at a novel technology stage. Safety devices and safety systems, i.e. gas detection, alarms and automated shut down, adapted from industrial applications are implemented. Teething troubles, including false alarms, and not optimized systems are still to be expected. The systems have to be followed up closely; remote control of hydrogen stations has still not reached a mature stage. Understanding of the needs of the users is an important task when designing high quality and safe infrastructures and vehicles. Instructions prepared in a form and language fit for the public user is a challenge.

8.0 FURTHER DEVELOPMENT OF THE USER INTERFACE

So far experiences from demonstration projects have revealed that both the HRS itself with all its equipment and systems need frequent follow-up. And so do the dispenser with its refuelling equipment. Hydrogen leakages have been detected and the need for identification of leakages and implementation of remedial actions are still rather frequent.

An absolute requirement of the dissemination of hydrogen refuelling stations for public use is that the user interface makes the HRS at least as safe and easy to use as refuelling stations for conventional fuels. This requires simple access to the station as well as simple, reliable and robust equipment and systems fit for all vehicles that may use the station.

To make hydrogen even more attractive as an alternative vehicle fuel in the public sector, solutions that promote more efficient refuelling and wider driving range are sought for. Technology and systems which enable shorter refuelling time and higher pressures need to be developed. The car industry has stated that the next generation of hydrogen fuelled cars will require 700 bar and wireless communication between the dispenser and the vehicle. Refuelling time and refuelling equipment such as nozzles and hoses fit for hydrogen at pressures at 400 – 700 bar must be developed. The future systems and equipment must handle short refuelling time without overheating the vehicle tank, i.e. the combination of fast filling and robust equipment needs to be addressed.

Whether the refuelling should be done manually or automated ought to be considered. Quantitative risk assessments have revealed that the risk increases with humans very close to the dispensing process. In the development of the future systems, technologies that minimise and even eliminate manual handling, should be considered. Already today current systems do not require a handhold refuelling (figure 9).

Figure 9: Refuelling of a fuel cell bus in Luxembourg (Photo: Hydro)

Motivation for more automated systems is less human operation, thus minimising the potential for human errors. With an automated system the risk related to people that stay very close – even between the dispenser and refuelling nozzle – can be minimised.

Modern cars are equipped with a range of electronic devices assisting the driver; crashing sensors, GPS systems and alarms helping the driver from driving too fast are installed. Hydrogen refuelling requires a fixed coupling between the dispenser and the vehicles, and technology enabling automated refuelling should also be evaluated. This may be a starting point of eliminating the need of any manual action in the refuelling operation. Development of high quality and safe user interface requires involvement and tight cooperation of all parties, i.e. HRS and vehicle manufacturers as well as manufacturers and suppliers of equipment and components for hydrogen services.

Maybe the only manual operation needed in the future should be related to the fuel payment. Even this can be done fully automated, if we are willing to see refuelling solutions that are totally different from what we see today. In any way a user interface that requires manual actions that may motivate the user to improvise must be prevented.

Challenges related to the user interface will be further discussed and handled by Hydro related to the new HRS recently established in Porsgrunn, Norway. This demonstration HRS is established within the HyNor project and operated by Hydro. The HRS with its user interface will be closely followed up by Hydro in order to gain experience for further development and improvement of hydrogen refuelling stations for public use. Risk assessments and work process assessments have been used to support design of the station and the user interface, and to give input to the refuelling procedure. The PDCA-methodology for continuous improvement is used during operation of the station.

9.0 CONCLUSIONS

Hydrogen stations and supply systems for public transport have been demonstrated in a number of European cities during the last four years. Experience from the demonstration projects CUTE and HyFLEET:CUTE has shown that safety related incidents are more frequent in the user interface than in the other parts of the hydrogen refuelling station. Equipment and component originally used for other gases have been modified to be used for hydrogen applications. The refuelling nozzles and hoses have given rise to incidents and deviations. Even though improvements have been made, equipment specially made for hydrogen applications needs to be developed.

Equipment and systems for the public transport sector must be safe, robust and easy to operate. The quality and safety approach to the establishment and operation of the stations within the demonstration projects is based on industrial experience and introduced to new applications and new customers. Risk assessments are used in design of the stations, but risk acceptance criteria relevant for the public arena should be developed. Incident reporting is an effective tool for continuous improvement using the PDCA-methodology.

The human factor must be duly addressed in the development of a safe and effective user interface. Any hazardous consequence of human behaviour and erroneous actions should be considered in design and layout of the user interface. In the development of the future systems, technology enabling automated refuelling should also be evaluated. This may be a starting point of eliminating the need of any manual action in the refuelling operation. Automated systems with less human operation will minimise the potential for human error, and the risk related to people during refuelling can be minimised. Development of high quality and safe user interface requires tight cooperation between all parties involved, i.e. the HRS and vehicle manufacturers as well as manufacturers and suppliers of equipment and components for hydrogen services. The importance of involving users' experience in design of the user interface is also emphasized.

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