RISK ANALYSIS OF THE STORAGE UNIT IN A HYDROGEN REFUELLING STATION

M. Casamirra; F Castiglia; L. Corchia; M. Giardina; C. Lombardo; G. Messina
Department of Nuclear Engineering, University of Palermo, V.le delle Scienze, 90128 Palermo
castiglia@din.unipa.it

ABSTRACT

Nowadays consumer demand for local and global environmental quality, in terms of air pollution and, in particular, greenhouse gas emissions reduction, may help to drive to the introduction of zero emission vehicles. At this regard, the hydrogen technology appears to have future market valuable potential. On the other hand, the use of hydrogen vehicles which requires appropriate infrastructures for production, storage and refuelling stages, presents a lot of safety problems due to the peculiar chemicophysical hydrogen characteristics. Therefore, safe at the most practices are essential for the successful proliferation of hydrogen vehicles. Indeed, to avoid limit hazards it is necessary to implement practices that, if early adopted in the development of a fuelling station project, can allow very low environmental impact, safety being incorporated in the project itself. Such practices generally consist in the integrated use of Failure Mode and Effect Analysis (FMEA), HAZard OPerability (HAZOP) and Fault Tree Analysis (FTA), which constitute well established standards in reliability engineering. At this regard, however a drawback is the lack of experience and the scarcity of the relevant data collection. In this work, we present the results obtained by the integrated use of FMEA, HAZOP and FTA analyses relevant, for the moment, the high-pressure storage equipment in a hydrogen gas refuelling station. The study, that is intended to obtain elements for improving safety of the system, can constitute a basis for further more refined works.

INTRODUCTION

Hydrogen is likely to be the most important future energy carrier for many stationary and mobile applications, with the potential to produce significant reductions of greenhouse gas emissions as well as improvements of the efficiency at the global scale, especially if renewable primary energy sources coupled with fuel cells are used to obtain it. Moreover it is particularly attractive for vehicle applications. As any vehicle fuel, hydrogen can be used in both fuel cells/electric drivetrains and internal combustion engines. At present the most attractive options for the onboard storage of hydrogen are as a compressed gas, a cryogenic liquid, or as a hydrocarbon on-board reformed to produce an hydrogen stream. The use of hydrogen vehicles which requires appropriate infrastructures for production, storage and refuelling stages, presents however a lot of safety problems due to its peculiar chemicophysical characteristics. In particular, the storage problems arise due to low hydrogen density; moreover, its low ignition temperature and flammability, over a wide range of concentrations, makes leaks a significant hazard for fire, especially in confined spaces. Therefore, safe at the most practices are essential for the successful proliferation of hydrogen vehicles.

Every different plant typology shows peculiar safety problems, to be in depth investigated from possible dangers and accidental risks point of view, which can lead to exposure of plant operators, people inside of it for refuelling, and people outside the station. Moreover, particular attention is to be devoted to the environment exposure in case of accident.

The above said practices to avoid hazards, if early adopted in the development of a fuelling station project, can allow very low environmental impact, safety being integrated in the project itself. Such practices generally consist in the integrated use of Failure Mode and Effect Analysis (FMEA), HAZard OPerability Analysis (HAZOP) and Fault Tree Analysis (FTA), which constitute well established standards in safety engineering. As well known, the most important objective of the FMEA is the prevention of problems through the identification of plant areas that are more subject to failures.

If a failure does occur, the FMEA may contribute to minimizing the effects of that failure. Concerning the HAZOP analysis, it allows to identify the relevant hazards and accidental scenarios. It is important to review all parts of the process, operational modes, maintenance, safety systems etc. During this analysis, hazards and possible accidental events (so called Top Event, TE) must be identified. Finally, FTA analysis, starting with a potential undesirable TE, allows to evaluate the probability of occurrence of the individuated TE.

In this work, we present the results of safety analyses obtained by using the FMEA, HAZOP and FTA integrated techniques relevant, for the moment, to high-pressure storage equipment in a hydrogen refuelling station near the city of Eureka, in California [1]. As well known, the on-site storage of hydrogen is an important aspect of fuelling station design and construction. In fact the storage systems accomplish two major roles in hydrogen delivery: regulation of delivery flow rate and increased working capacity.

The study, that is intended to obtain elements for improving safety of the system, can constitute a basis for further more refined works.

2.0 PLANT DESCRIPTION

The reference system consists in a hydrogen power park, to be realized near the city of Eureka, in California [1], designed at the Humboldt University. This system is foreseen to provide thermal and electrical power as well as gaseous hydrogen for car refuelling. The produced hydrogen feeds a CGH2 type refuelling station: hydrogen is produced in situ and stored in form of compressed gas by a three-stage compressor and is sent to three storage vessels, respectively, at low (152 bar), medium (220 bar) and high pressure (460 bar). Hydrogen compressor is endowed with various compression stages due to the needed very high pressure as well as to the peculiar thermal-physical hydrogen properties. In the examined plant for this study, the three stages compressor is equipped with internal and external pressure switches that operate based on downstream pressure. The external pressure switch (PS2), located outside of the compressor, ensures that the compressor switches off only when the storage pressure equals the relevant set point. Moreover, a pressure regulator (PR) in the compression unit reduces unwanted higher pressure gas in process line.

The storage vessels are protected by pressure relief devices (a mechanical valve and a solenoid one placed in parallel to vent the process gas in the case of excess pressure and malfunction of the control system), which help to assure that the maximum allowable pressure is not exceeded. All of the pressure relief devices are set 10 percent below the maximum allowable working pressure. The storage pipelines are equipped with pressure gauges (PG), connected with the pressure transducers (PT), and solenoid valves (SV), actuated through a Programmable Logic Controller (PLC). Such an unit is also used to control major safety functions of the station, including regulation of the dispenser interactions. This system is equipped by backup batteries to ensure the PLC functionality in case of electrical power loss.

Dispensers able to refuelling vehicle tank by 4,5 kg 345 bar pressure hydrogen in 7,2 minutes, are employed. The refuelling is performed in “cascade”: when the vehicle is connected to the dispenser, PLC makes solenoid valve of the storage low pressure gas line to open. If necessary the operation is completed by the other stages at higher pressures. This allows to regulate the hydrogen out-flow from storage vessel, optimizing the refuelling time. Other advantage is to reduce abrupt pressure change in the distribution network. When the storage is unavailable the refuelling can be accomplished by hydrogen from gas cylinders wagon. Finally, an appropriate inert gas feeding allows to purge the circuit systems.

Manual emergency shut-down, “panic buttons”, are strategically placed in side as well outside the facility to initiate immediate shut-down of all processes hydrogen lines, if needed.

Finally, in order to operate emergency systems functions, an emergency standby engine-driven generator allows to backup the external electric power, the emergency lighting, and the fire pumps, in the event of a power failure or a fire, which interrupts the normal grid-provided electricity supply.

Figure 1 shows the above described compression and storage systems.

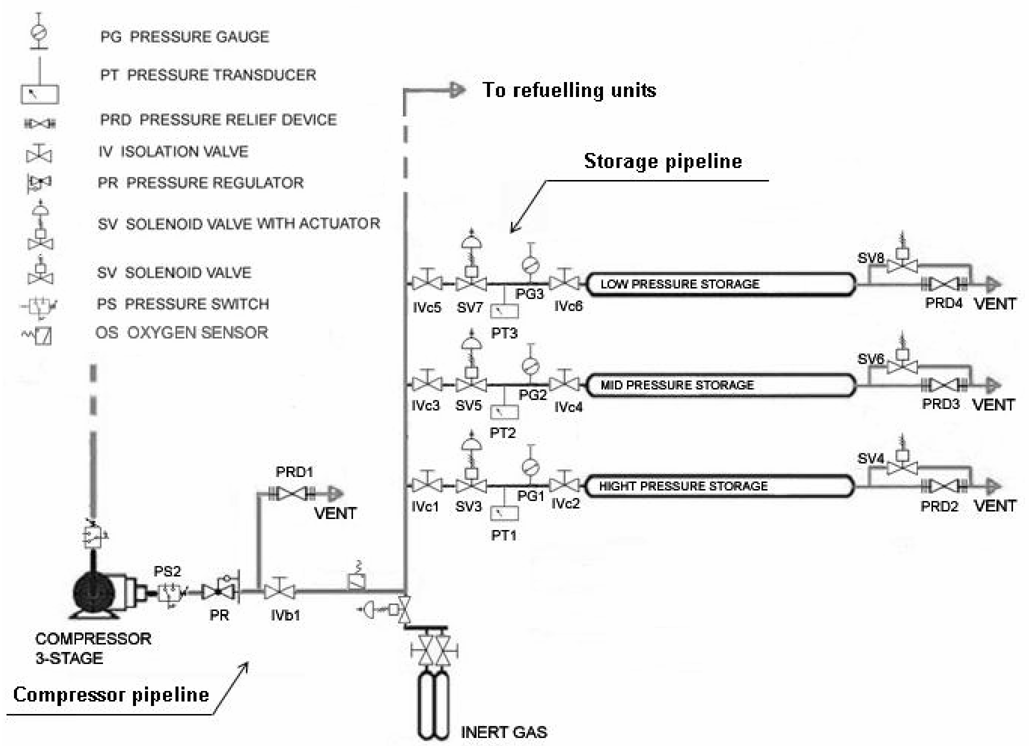

Figure 1. Compression and storage units of the plant.

3.0 PLANT RISK ANALYSIS

As above said, in this work we present the results obtained by the integrated use of FMEA, HAZOP and FTA analyses relevant the gaseous hydrogen high-pressure storage equipment in a refuelling station. Each analysis typology entailed the compilation of some 50 FMEA forms, two more forms for a limited HAZOP study, and finally the FTA evaluation of the frequency of two undesirable accidental events, namely hydrogen loss in the environment and overpressure of the storage vessel, individuated through the application of the HAZOP technique.

As one can see, because of the very cumbersome forms number, in the following we confine ourselves to report only few samples of the obtained results for each analysis.

3.1 FMEA analysis

As it is known, the FMEA analysis [2] is developed by studying the failure that might affect the system components under consideration. When the failure modes are identified, it is necessary to recognize the associated causes as well as the consequences in the component itself and in the system on the whole, corrective actions have to be suggested to eliminate or reduce the potential for occurrence. Moreover, this analysis uses the occurrence probability and detectability in conjunction with a severity criteria to develop a Risk Priority Number (RPN), a critical indicator which allows to recognize the hazard level of the failures, obtained by multiplying the Severity, Occurrence and Detection ranking levels [3], and resulting in a scale from 1 to 1000: obviously, a smaller RPN number is the better.

Note that in the present analysis much failure modes relevant the mechanical and solenoid valves in storage vent safety system, the compressor and the relevant pressure switches, result to present the higher RPN values.
The FMEA forms, reported in Tables 1 and 2, refer to some failure modes of the above mentioned component, in our judgement believed to be the most important.

Table 1. FMEA form relevant solenoid valves.

SOLENOID VALVE												
N°	**Failure mode**	**Operating phase**	**Local effects**	**Effects on the system**	**Detection methods**	**Measures to mitigate**	**Observation**	**Failure rate λ (y^{-1})**	**OCC**	**SEV**	**DET**	**RPN**
Unit : Vent safety system of the high, medium, low pressure storage vessels. **Process :** Filling of storage vessels at high, medium, and low pressure, respectively.												
Component : SV4, SV6, SV8 Solenoid valves **Description :** They enable the safety vent of the high, medium and low pressure storage vessels**,** respectively, to open. The solenoid valves are open or closed by PLC. The valves control is enabled by electrical pressure transducer signal, located at the storage vessel entrance. The valve is open if the PRD mechanical valve is locked.												
1	Fails to open	Closed	Local pressure increase	Pressure increase in storage vessel	Pressure increase revealed by storage pipe line pressure gauge (**PG**)	PLC switches off the compressor & closes solenoid valve (**SV**) of storage vessel in filling phase	-	$2{,}27 * 10^{-2}$	1	7 (II)	3	21
2	Fails to close	Open	Gas flow vent	Pressure decrease in storage vessel	Pressure reduction revealed by storage pipe line pressure gauge (**PG**)	-	Dangerous failure mode, hydrogen being continuously vented in environment	$6{,}06 * 10^{-2}$	1	7 (II)	3	21
5	Solenoid fault	Open	Valve closes & hydrogen flow stopped	Pressure increase in storage vessel	Pressure increase revealed by storage pipe line pressure gauge (**PG**)	-	-	2	4	7 (III)	3	84

Table 2. FMEA form relevant pressure switch .

PS2 – PRESSURE-SWITCH												
N°	**Failure mode**	**Operating phase**	**Local effects**	**Effects on the system**	**Detection methods**	**Measures to mitigate**	**Observation**	**Failure rate λ (y^{-1})**	**OCC**	**SEV**	**DET**	**RPN**
Unit : Compression system. **Process :** Filling of storage vessels at high, medium, and low pressure, respectively.												
Componente : PS2 PRESSURE-SWITCH **Description:** Pressure switch must ensure compressor switch off when downstream pressure equals the storage set point.												
1	Switch fault	On	Uninterrupted pressurized gas delivering.	Storage pressure increase	Pressure increase revealed by storage pipe line pressure gauge (**PG**)	PLC switches off compressor & closes the solenoid valve **(SV)** of storage vessel in filling phase Vent of relief valve (**PRD1)** occurs, if necessary	Vent actuates when the storage relief pressure set point is exceed	$1{,}31 * 10^{-2}$	1	7 (II)	3	21
2	Delayed operation	On	Uninterrupted pressurized gas delivering.	Maximum pressure in storage vessel could be exceeded	High storage pressure revealed by storage pipe line pressure gauge (**PG**)	PLC switches off compressor & closes the solenoid valve **(SV)** of storage vessel in filling phase Vent of relief valve (**PRD1)** occurs, if necessary	Vent actuates when the storage relief pressure set point is exceed	$1{,}75 * 10^{-2}$	1	7 (II)	3	21

3.2 HAZOP analysis

The analysis goes on with the classic HAZOP one that allows to perform the study of the process into consideration. This study is performed by analyzing process variables deviations occurring at suitable system “nodes”. A single point P1, located on the pipeline between compressor and storage units, has been chosen as internal node (see Figure 1). The hydrogen flow rate and pressure have been chosen as parameters to be examined.

The analysis allowed to individuate the following Top Events:

- hydrogen loss in the environment (TOP1);
- overpressure of the storage vessel (TOP2).

The obtained results, relevant the study of the above described physical parameters deviation are reported in Tables 3 and 4.

Table 3 . HAZOP Analysis in node P1 relevant the deviations of the hydrogen flowrate parameter.

HYDROGEN REFUELLING STATION						
Node P1: Communication line between compressor unit and storage vessels at high, medium, and low pressure. **Process:** Filling of storage vessels at high, medium, and low pressure, respectively.						
Deviation	**Parameter**	**Causes**	**Consequences**	**Protections**	**Comments**	**TOP**
No	Hydrogen flowrate	Compressor Failure	Pressure vessel filling interruption.	PLC closes storage unit solenoid valves	Filling interruption.	
		Isolation valve Ivb1 in compression line closed.	Compression line pressure increase.	PLC closes storage unit solenoid valves. PRD1 vent actuates. PS2 switches off the compressor.	Unwanted compression line pressure increase if PRD1 vent fails.	
Greater than		PS2 switches off the compressor at pressure higher than the storage set point.	Storage vessel overpressurization.	Pressure gauge & pressure transducer reveal overpressure. PLC switches off the compressor & closes the storage unit solenoid valves.	If pressure is too high, storage vent actuates.	
		Compressor gas high flow & PR pressure regulator fails.	Pressure increase & possible storage vessel overpressurization.	PS2 switches off the compressor. Pressure gauge & pressure transducer reveal overpressure.	If pressure is too high, storage vent actuates.	
Less than		PS2 switches off the compressor at pressure lower than the storage set point	No complete vessel filling.	PLC closes the storage unit solenoid valves.	No complete vessel filling.	
		PR pressure regulator fails.	Delay in storage vessel filling.	No.	-	
		Hydrogen leak.	Loss of hydrogen in environment .	PLC, activated by hydrogen sensors, switches off the compressor & closes the storage unit solenoid valves.	If adverse conditions happen, ignition is possible.	**TOP 1**

Table 4 . HAZOP Analysis in node P1 relevant the deviations of the storage pressure parameter.

HYDROGEN REFUELLING STATION						
Node P1: Communication line between compressor unit and storage vessels at high, medium, and low pressure. **Process:** Filling of storage vessels at high, medium, and low pressure, respectively.						
Deviation	**Parameter**	**Causes**	**Consequences**	**Protections**	**Comments**	**TOP**
Greater than	Storage pressure	PS2 switches off the compressor at pressure higher than the storage set point	Storage vessel overpressurization.	Pressure gauge & pressure transducer reveal overpressure. PLC switches off the compressor & closes the storage unit solenoid valves.	If pressure is too high, storage vent actuates.	**TOP 2**
		Compressor gas high flow & PR pressure regulator fails.	Pressure increase & possible storage vessel overpressurization.	PS2 switches off the compressor. Pressure gauge & pressure transducer reveal overpressure.	If pressure is too high, vent actuates.	
Less than		PS2 switches off the compressor at a pressure lower than the storage set point.	No complete vessel filling.	PLC closes the storage unit solenoid valves.	No complete vessel filling.	
		PR pressure regulator fails.	Delay in storage vessel filling.	No	-	

3.3 FTA analysis

For the sake of brevity, we confine to consider only the Top Event indicated as TOP2, that is: storage vessel overpressure during the hydrogen filling phase. The hypothesized accidental scenario can be schematized by the following main undesired causes:

- exceeded storage pressure set point;
- PLC failure.

It is to be emphasized that the PLC failure can affect all the accidental events bringing to exceed the storage pressure set point, therefore such an event has been considered a common cause failure one and directly connected to the Top Event gate.

As for exceeded storage pressure set point accidental event, it can result by:

- storage vent safety system failure;
- pressure increase due to compression unit failure;
- storage pipe line pressure control system failure.

The failure of the storage vent safety system can occur due to mechanical valve fault (PDR) as well as due to solenoid valve faults (SV).
On the other hand, the pressure increase due to compression unit fault can occur due to malfunction of the outside compressor pressure switch (PS2) or else due to compressor malfunction accompanied by pressure regulator failures.
Finally, the failure of the pressure control system (pressure gauge and pressure transducer) can be due to erroneous output from pressure gauge or else to absence of signal by the pressure measurement system.

Leaving out to describe further details, we report in Table 5 all the failure rate data [4] used for the analysis.

The above depicted scenarios are resumed in the fault tree reported in Figures 2÷5.

Table 5. Failure data used for the analysis.

Name	Failure rate (h^{-1})	Comment
Event(1)	4.300e-006	Mechanical valve (PRD) fault
Event(10)	1.500e-006	PS2 switch fault
Event(11)	5.300e-007	PR Delayed operation
Event(12)	5.300e-007	Erroneous calibration
Event(13)	3.200e-006	Erroneus output from Pressure guage (PG)
Event(14)	8.300e-007	PLC failure
Event(15)	5.700e-007	No signal from pressure guage (PG)
Event(16)	5.400e-007	PT rupture
Event(19)	1.700e-004	Internal pressure switches fault
Event(2)	2.280e-004	Solenoid fault
Event(3)	1.600e-006	Loss of external electric power
Event(4)	2.590e-006	Valve locked close
Event(5)	1.570e-006	PR Rupture
Event(7)	1.800e-005	Emergency power fails to start
Event(8)	4.410e-006	High gas flow due to compressor degradation
Event(9)	2.000e-006	Too delayed PS2 switch operation

The analysis, carried out by using STARS code [5], gives the following result for the Top Event frequency:

$$P(TE) = 2.9*10^{-7}\ y^{-1}$$

The number and the maximum order of the Minimal Cut Set (MCS)has been also evaluates. These ones are reported in Figure 6 as histogram, according to the probability of occurrence as well to the cut set order.

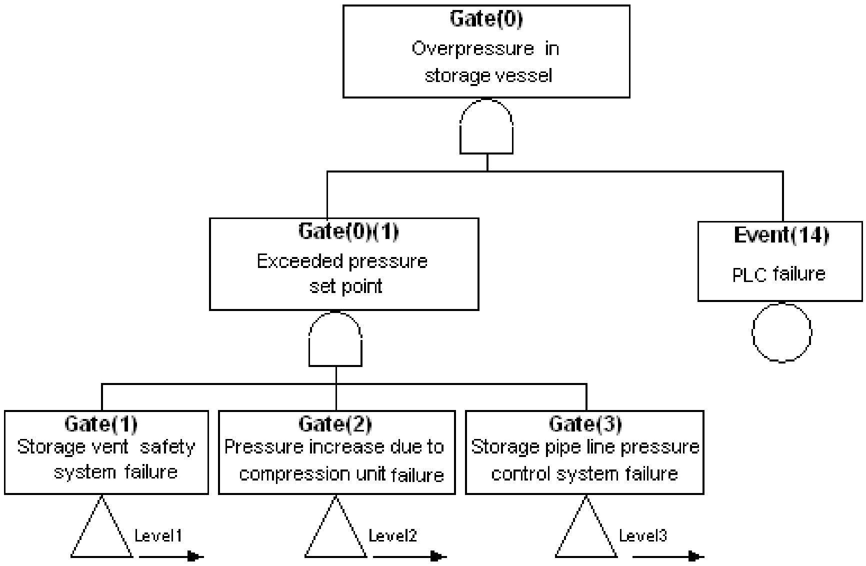

Figure 2. Storage vessel overpressure Top Event undeveloped fault tree.

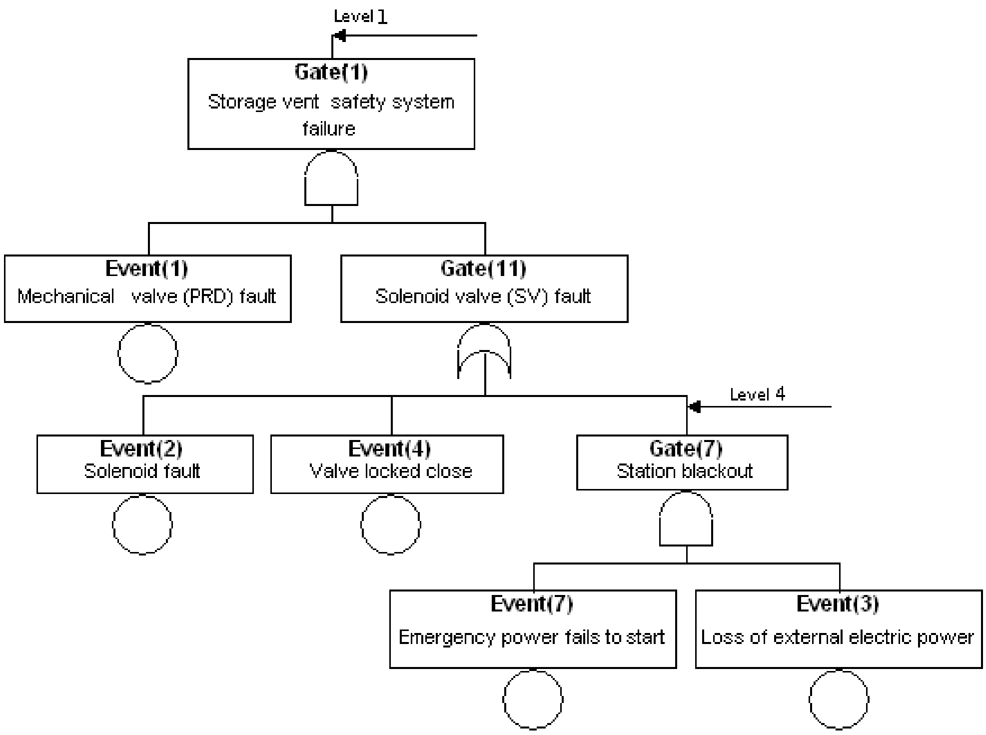

Figure 3. Storage vent emergency system failure sub–fault tree.

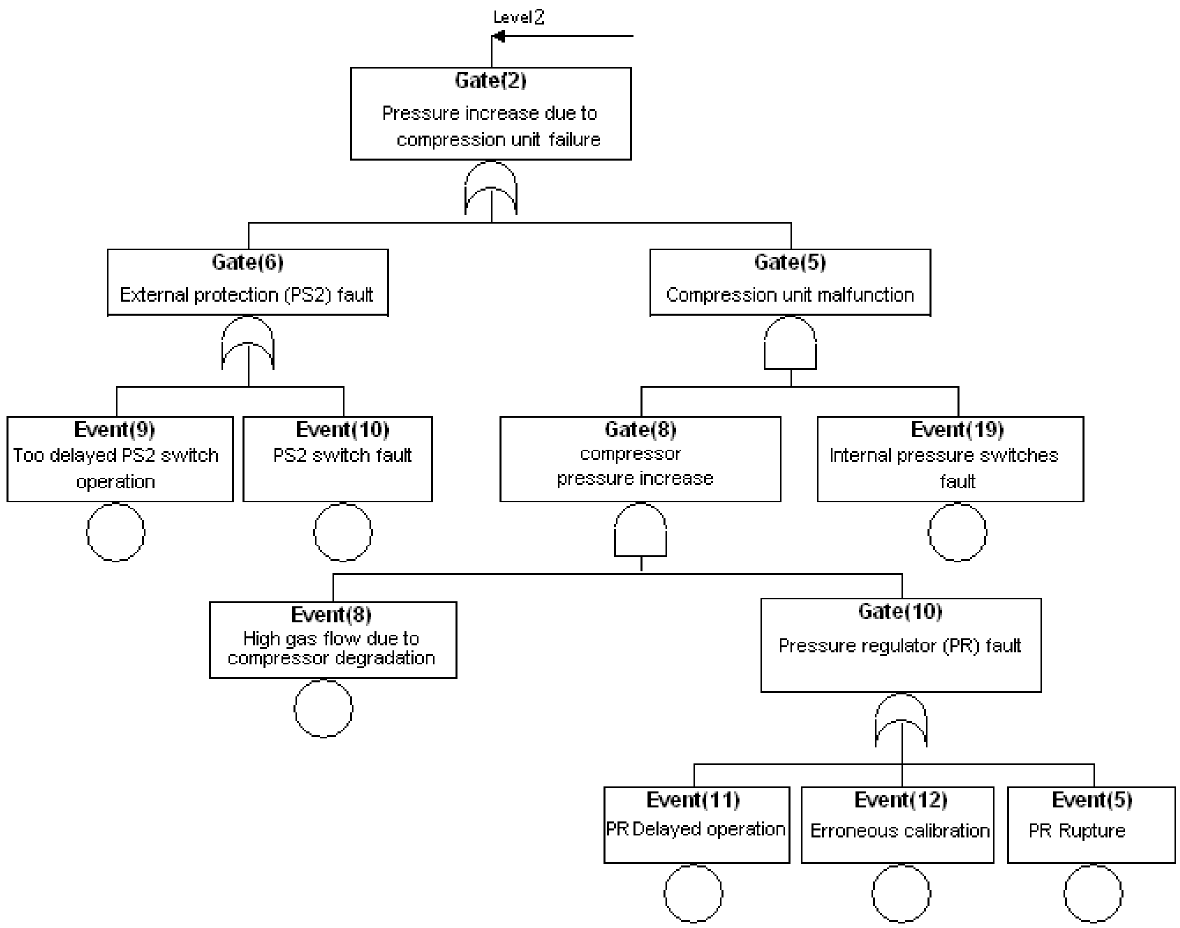

Figure 4. Pressure increase due to compression unit failure sub – fault tree.

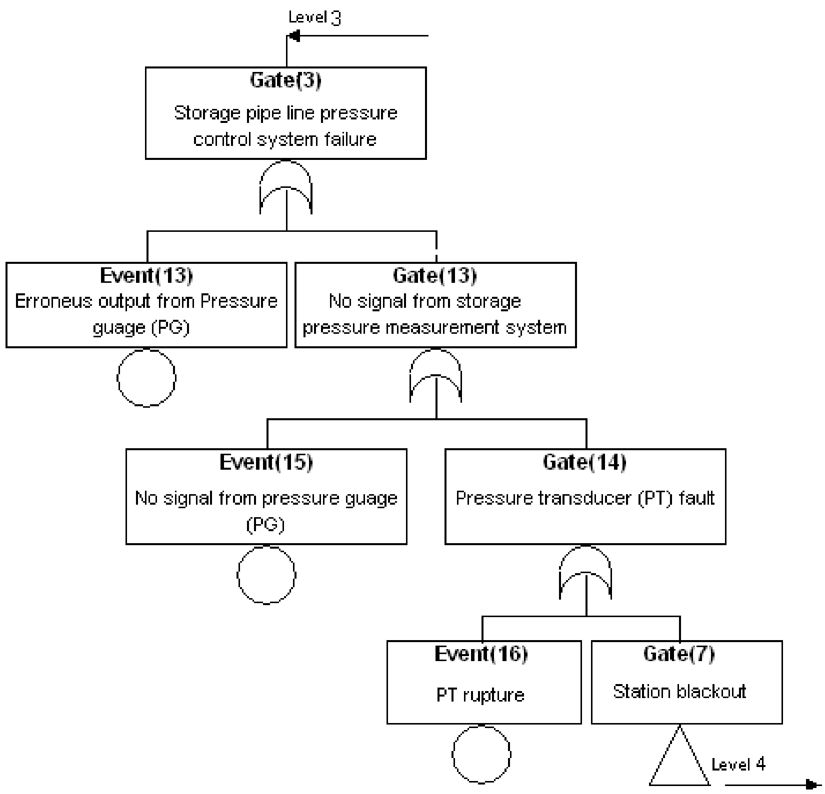

Figure 5. Storage pipeline pressure control system failure sub – fault tree.

It is worth to note that there are fourteen MCSs of fifth-order and as much as forty-two MCSs of seventh-order. This in some way explains the resulting very low Top Event probability.

Among the fifth-order MCSs, the one having the higher unavailability includes the following events:

- too delayed pressure switch (PS2) operation;
- solenoid fault in solenoid valve (SV);
- erroneous output from pressure gauge (PG);
- mechanical valve fault (PRD);
- PLC failure.

Remember that just these failure modes have been recognized to have the higher RPN values in the FMEA analysis. Moreover the criticality of these failure modes is confirmed by the sensitivity analysis which shows the basic events contribute to the system unavailability carried out by using the Barlow-Proschan importance indexes. Figure 7 represents the first ten events exhibiting the higher values of these indexes.

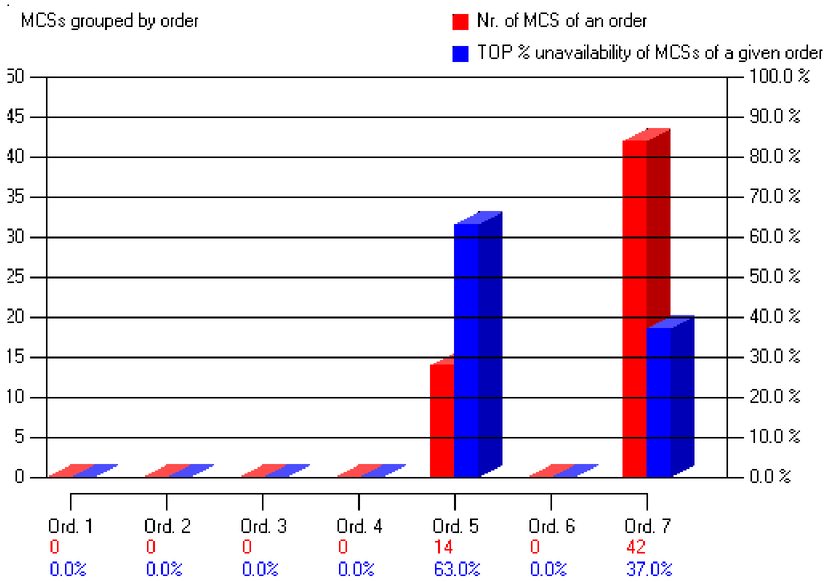

Figure 6. MCS identified by the STARS code.

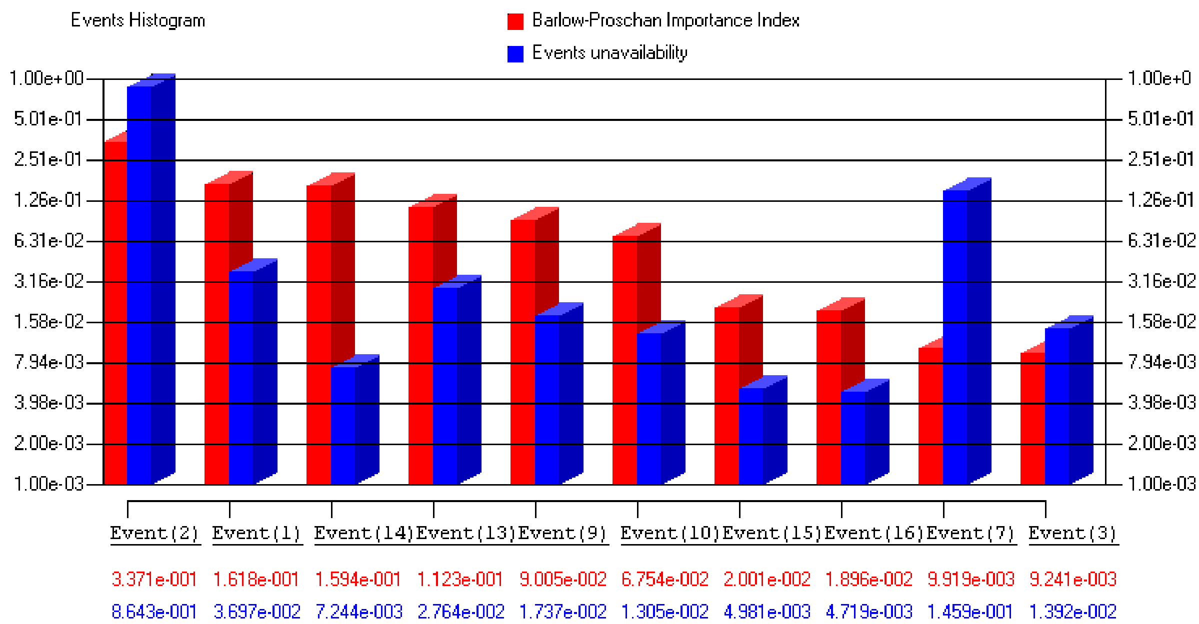

Figure 7. Barlow-Proschan importance indexes calculated by the STARS code.

4.0 CONCLUSION

In the present paper samples of the obtained results of the integrated use of the most effective risk analysis techniques (namely FMEA, HAZOP analyses, and FTA) are reported. These analyses concerned with the high-pressure storage equipment in a hydrogen refuelling station.

In particular:

- The FMEA technique evidenced the components exhibiting considerable high potential to failure;

- The HAZOP analysis allowed to individuate two undesirable accidental scenarios, that is: leak of hydrogen in the environment (TOP1) and overpressure of a storage vessel (TOP2);

- The FTA analysis, for the moment carried out to deepen the study of only the last undesired event (TOP2), resulted in a frequency occurrence as low as $2.9*10^{-7}$ y^{-1}. Therefore, borrowing the accident categorization from nuclear reactor technology, this Top Event behaves as a quite rare limiting fault.

REFERENCES

1. Evolution Energy Systems: Design Proposal for a Hydrogen Power Park Eureka, California; 2005, Schatz Energy Research Center.
2. Reliability maintainability and risk, Sixt Edition, Dr David Smith, Buherworth Heinmann.
3. Failure Mode and Effects Analysis (FMEA): A Guide for Continuous Improvement for the Semiconductor Equipment Industry; SEMATECH Technology Transfer #92020963B-ENG.
4. Offshore Reliability Data Handbook, 2nd edition; OREDA .
5. STARS Study User Guide, 1990-1995, Microsoft Corp.

Work supported by: Ministero dell’Istruzione dell’Università e della Ricerca (MIUR): funds “Progetti di Rilevante Interesse Nazionale (PRIN)”, 2005.