SIMPLIFIED METHODS FOR THE ASSESSMENT OF FIRED BLEVE HAZARDS

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ABSTRACT

An approach was developed for the calculation of escalation probability caused by fires. Simplified models were obtained for the estimation of the vessel time to failure with respect to the radiation intensity on the vessel shell. The time to failure was compared to a reference time required for effective mitigation actions and related to the escalation probability. The escalation probability model obtained by this approach was applied to case-studies in order to evaluate the contribution of escalation triggered by fires to the individual risk index.

1.0 INTRODUCTION

Ignition of accidental releases of flammable substances leading to jet fires may cause secondary events with catastrophic consequences due to flame impingement on equipment and pipes. Several accidents occurred in the past ten years in the chemical and petrochemical industry present these features. The analysis of the MHIDAS database [1] evidenced that fireballs are among the more severe accidental scenarios involving pressurized storages of flammable substances. 31% of reported accidents actually affected LPG storage vessels, and 20% of accidents involved pressurized vessels containing flammable gases. Accident data analysis also allowed the identification of the primary caused of these accidents. These resulted mainly related to jet fire impingement (24% of reported accidents) or to fire engulfment caused by compressed gases or liquid fuels. Past accident data analysis thus evidence that the BLEVE hazard is a critical issue in the risk management within the offshore chemical and petrochemical industry and, more generally, in the risk management of storage vessels containing pressurized flammable gases. The need for the development of safe hydrogen storage technologies causes a renewed interest in the development of strategies for the prevention and the mitigation of BLEVE hazard. As a matter of fact, a preliminary safety assessment of hydrogen technologies evidences that fired BLEVEs are among the more severe accidents that may be expected. The prevention of fired BLEVE hazards requires the preliminary assessment of the possible escalation events triggered by primary jet fires and pool fires, and the consequent application of inherent, passive and active strategies for the control and the reduction of the risk associated to hydrogen storage vessels. The present contribution focuses on the development of specific strategies for the protection of hydrogen storages from fired BLEVE events.

2.0 FIREBALL AND BLEVE HAZARD FOR PRESSURIZED VESSELS

The use of hydrogen as an energy vector will lead to the wide diffusion of small and medium size pressurized hydrogen storage vessel. It is well known that fireballs are among the more severe scenarios that may affect this type of storage installations. This was confirmed by the analysis of the MHIDAS database [1]. The database reports 269 fireball events, 101 of which following a BLEVE. Table 1 shows the number of fatalities reported for the reported events. As shown in the table, 31 events (11.5 %) resulted at least in 1 fatality. Figure 1 evidences that the fireball scenario is typical of storage vessels, while figure 2 shows that these events involve mainly 33% of reported accidents actually affected LPG storage vessels (31%), while the 20% of the reported accidents involved pressurized vessels containing flammable gases.

Table 1: Number of fatalities in the fireball events reported in the MHIDAS database

Fatalities	n° of events	%
n.a.	82	30.5
0	81	30.1
1	31	11.5
2	19	7.1
10-19	14	5.2
20-29	4	1.5
30-39	1	0.4
50-59	1	0.4
90-99	1	0.4
100-109	1	0.4
200-209	2	0.7
500-509	1	0.4
1000-1009	1	0.4

The quantities of hazardous substances usually involved in Accident data analysis also allowed the identification of the primary causes of these accidents. As shown in figure 3, these resulted mainly related to jet fire impingement (24% of reported accidents) or to fire engulfment caused by compressed gases or liquid fuels. Figure 4, reporting the quantities of hazardous substances typically involved in fireball accidents confirms that this accidental scenario may as well involve small and medium size storage vessels.

Therefore, the results of past accident data analysis confirms that the safety management of hydrogen pressurized storage vessels should include the prevention and the mitigation of the hazards due to fireball accidental scenarios. Data in figure 3 confirm that fireballs are mainly secondary scenarios, due to a primary fire event. Thus, the management of the fireball hazard should address the prevention of primary fire events (including low-severity fires), and the fire protection of storage vessels. The second issue requires an optimization among active and passive protection strategies, aimed to enhance the fire resistance of the vessel. In this framework, two key-issues should be approached: i) the estimation of the time to failure of vessels involved in fire scenarios; and ii) the assessment of the performance of passive protection systems.

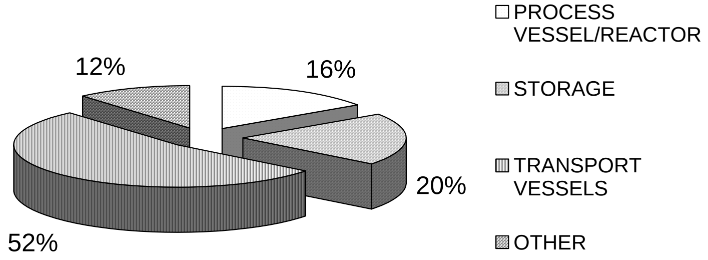


Figure 1: Equipment involved in fireball scenarios

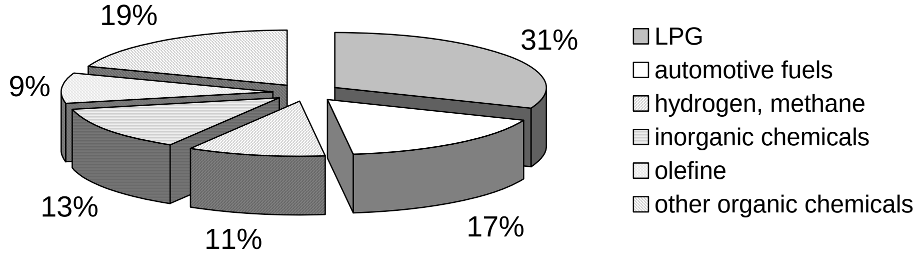


Figure 2: Substances involved in fireball scenarios

3.0 THE ESTIMATION OF VESSEL TIME TO FAILURE

3.1 Simplified correlations for time to failure

The estimation of the “time to failure” (ttf) of vessels under external fire conditions is a complex task, that requires the modeling of the radiative heat flow from the fire to the vessel wall, wall temperature-time profile, vessel internal pressure and the application of failure criteria. Clearly, a complete approach to the problem is not feasible in the framework of fireball and BLEVE hazard management of medium and small storages, where a straightforward assessment is required.

In the present approach, simplified correlations were obtained for the ttf as a function of the radiation intensity, the radiation mode and the vessel type. The correlation were based on an extended modeling approach, aimed to the development of an extended dataset of vessel ttfs validated on the basis of the available experimental data reported in the literature. The correlations may be used for a conservative estimate of the time to failure, as well as for an assessment of the radiation threshold value below which no failure is expected. It is important to remark that this threshold resulted highly dependent on the on-site emergency management.

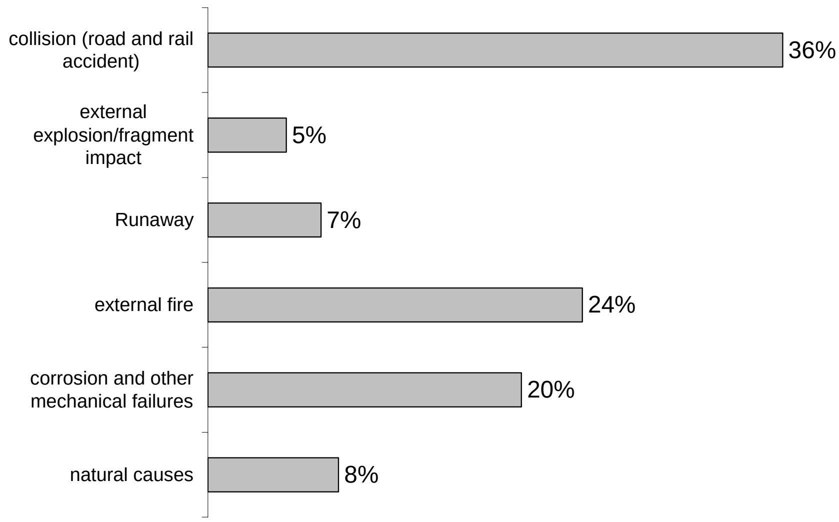


Figure 3: Primary event triggering fireball scenarios

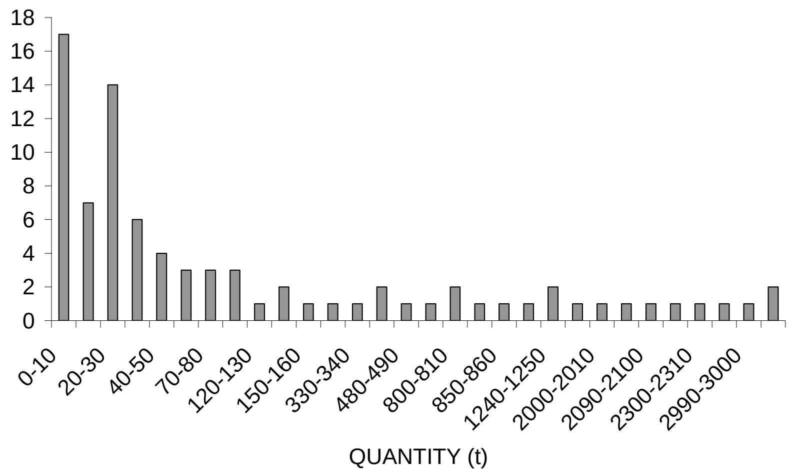


Figure 4: Quantities of flammable substances involved in fireball scenarios

3.2 Modeling vessel behaviour under external fire conditions

The first step required for the procedure was the development of validated models for the vessel time to failure. Fire may affect a process or storage vessel by one or more than one of the following modes: i) distant source radiation; ii) full or partial fire engulfment; and iii) jet fire flame impingement.

Modelling vessel time to failure in these three situations is extremely difficult given the high complexity of the flame geometries. The wall temperature behaviour in a vessel exposed to an external fire would require a detailed 3D analysis of the thermal flux over the vessels shell, of the thermal gradients in the fluid contained in the vessel and of the effects due to the mixing of the content due to the natural convection. However, a model based on this approach would require a prohibitive run time, not justified in a QRA framework due to the uncertainties that usually affect the characterization of the fire scenario. In this specific context, a simplified model able to yield a conservative estimation of the time to failure by a straightforward approach would be more useful. The model developed in the present study was based on a lumped approach for the modelling of the time and temperature profile, but was improved by an extended validation work, based on an experimental data set for the vessel time to failure, extended by the use of a 3D finite element model implemented for this purpose.

The development of the lumped model was based on thermal nodes modelling. Depending on the fire attack condition, this approach attempts to divide the equipment in different zones (or nodes), each of which can be described by a simple set of parameters. The parameters represent physical quantities (e.g. temperature, pressure, thermal conductivity, etc.) averaged over each node. Conservation conditions at the boundaries between different region, together with global conservation laws, lead to a system of equations which determines the parameters of interest and in particular the temperature at each node. This allows the calculation of temperature-time profiles as a function of the radiation mode and intensity on the vessel. The estimation of these parameters allows the evaluation of the mechanical stress at which each zone of the vessels shell is subjected and to compare it with the admissible tensile strength of the vessels material (that is strictly dependent on the material temperature). The failure conditions are strictly dependent on the structural design: geometry, material, boundary condition. For the equipment of interest (horizontal cylindrical vessels, vertical cylindrical vessels, etc.) subjected to an intense heat flux the failure conditions that must be taken into account are the wall-thinning due to hoop stress and high temperature material degradation, and instability. A specific failure criteria should be associated to each type of failure to establish when there is the failure of the vessel giving a loss of containment. A failure criteria is generally derived by a direct comparison between parameters representative of the stress field over the vessels shell and parameters representative of the tensile strength of the material or of the limit stability of the structure. Thus, the failure criteria require the knowledge of the stress field over the vessel shell and on the boundary structures, that may be calculated only by more detailed modelling approaches. This means that with a lumped model only simplified empirical failure criteria may be adopted. An extended validation of the simplified model is required to ensure the reliability of the failure criteria implemented, in particular for atmospheric vessels, where the internal pressure is not the main factor affecting the vessel failure. A first set of validation runs was carried out using experimental data available in the literature. Although a significant number of case-studies resulted available, in particular for pressurized vessels, the number of available experiments was not sufficient to carry out an extended validation covering the entire field of vessel geometries and of radiation modes and intensities. Thus, a finite element model was developed and validated on the basis of the experimental data. The finite element model was used to generate a second data set used for the validation of the simplified lumped element model. The model was developed using a finite element code (ANSYS Version 5.5) with which a detailed simulation of the thermal and mechanical conditions on vessel shells under fire radiation was possible. The model allowed a detailed simulation of the radiation mode, of the wall temperature and of the stress over the vessel shell. Adopting proper failure criteria it was possible to use the knowledge of the temperature and of the stress conditions in each point of the structure to estimate more precisely the time to failure. The first step in the simulations was the detailed calculation of the temperatures on the vessel shell as a function of time and radiation mode. A detailed definition of the radiation conditions on vessel shell was possible. Figure 5 shows an example of detailed temperature simulations for pressurized vessel under radiation due to flame engulfment. Temperature maps as those shown in figure 5 were obtained for each time step of the simulation.

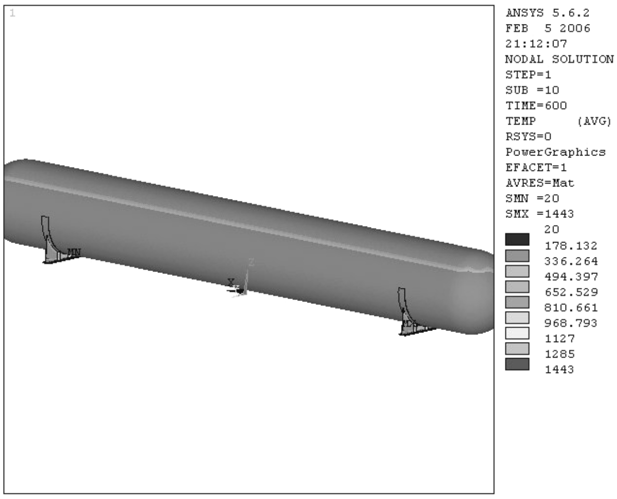


Figure 5: Detailed simulation of the temperature on the shell of a 100 m^3 pressurized vessel under radiation due to flame engulfment (120 kW/m^2, 600s)

The second step of the modeling was the calculation of the stress field as a function of the local temperatures and of the other loads present on the equipment shell. Figure 6 shows an example of the maps representing the stress field acting on the equipment shell obtained from the temperature simulations in figure 5. The calculation of the detailed temperature and stress maps allowed the application of the correct failure conditions and thus a quite accurate calculation of the equipment time to failure, also accounting for the decrease in the allowable stress due to the high temperatures of the vessel walls. The comparison of the results of the simulations carried out with the first set of experimental validation data showed that the predicted times to failure were always conservative and showed a relative error lower than 10%. Thus, the finite element code may be reasonably used to extend the validation of the simplified lumped model.

The validation of the lumped model carried out using both the experimental and finite element data for the vessel time to failure pointed out that the lumped model gives always credible and conservative values for the time to failure of the vessels. A 15% average relative error is present between the ttf calculated by the lumped model and those obtained by the ANSYS simulations. In the failure criteria adopted it is necessary to consider the admissible tensile strength of the material. If this parameter is not directly available, it is possible to use the yield strength of the material. Using the ultimate tensile strength of the material more credible, but not always conservative values are obtained for the time to failure.

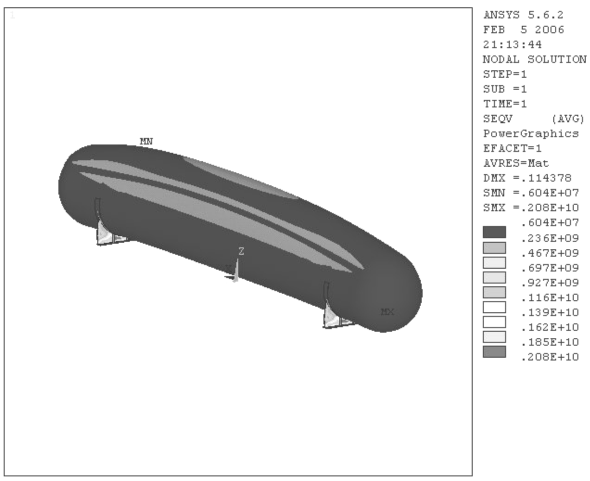


Figure 6: Detailed simulation of the stresses on the shell of the 100 m^3 atmospheric vessel under the conditions shown in figure 5

3.3 Estimation of vessel time to failure

In the risk management of BLEVE and fireball hazard, a huge number of possible scenarios should be assessed. Thus, a very high number of simulations may be required. Even if the lumped model is characterised by a relatively low computational time, its use may require a relevant effort, also considering that the model, although simplified, requires to define and input several parameters of each vessel and radiation mode considered.

The availability of further simplified tools to carry out a preliminary assessment of the time to failure is thus useful, in particular to identify the credible domino targets in a complex layout. To face this problem, a specific approach was used to define simple analytical functions for the evaluation of the time to failure of the equipment exposed to fire. The more important categories of equipment involved in external fires were identified, and their geometrical characteristics were defined (shape, range of sizes, etc.). Vessel sizes were obtained from typical design data used by engineering companies in the oil and gas sector. The design data of the atmospheric tanks were based on API 650 standards, while the volumes and diameters were based on data from several oil refineries. In the case of pressurized vessels, the volumes and diameters were derived from vessels typically used for LPG, vinyl chloride, chlorine and ammonia pressurized storages. Cylindrical vessels with horizontal axis and design pressures of 1.5, 2.0 and 2.5MPa were considered. The design data were verified with respect to section VIII of the ASME codes, and the relief valves were considered to provide the vent area required by API RP 520 standards. In order to obtain conservative data, no thermal insulation and no active mitigation system was considered for both sets of vessels.

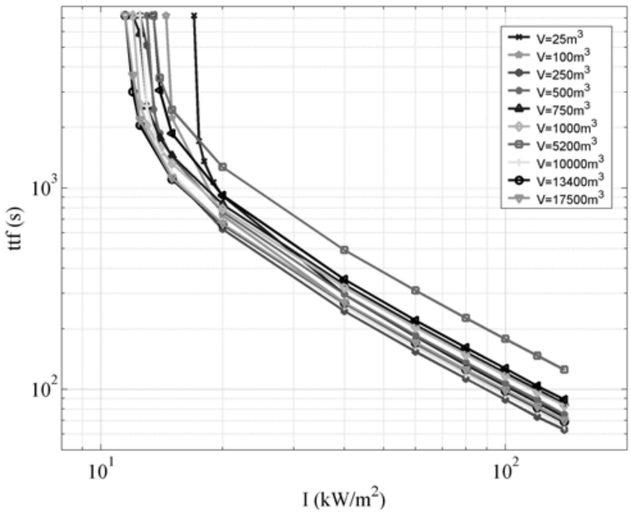


Figure 7: Times to failure obtained for vertical cylindrical atmospheric vessels under distant source radiation

The more credible primary events were selected, the types of radiation modes and a range of credible radiation values were defined. An extended matrix of case studies was thus defined. The lumped model was used to analyze each case study, estimating the time to failure of the selected equipment exposed to the selected type of fire attack and to different radiation values. A fitting procedure was implemented to obtain specific analytical functions that directly relate the time to failure of the equipment (ttf) to the value of the radiating heat flow (I):

$$\log_{10}(\mathrm{ttf}) = a \cdot \log_{10}(I) + b\,, \qquad (1)$$

where the a and b coefficients depend on the vessel type and geometry and the radiation mode. The a and b coefficients may thus be calculated from the fitting of simulation results to eq.(1).

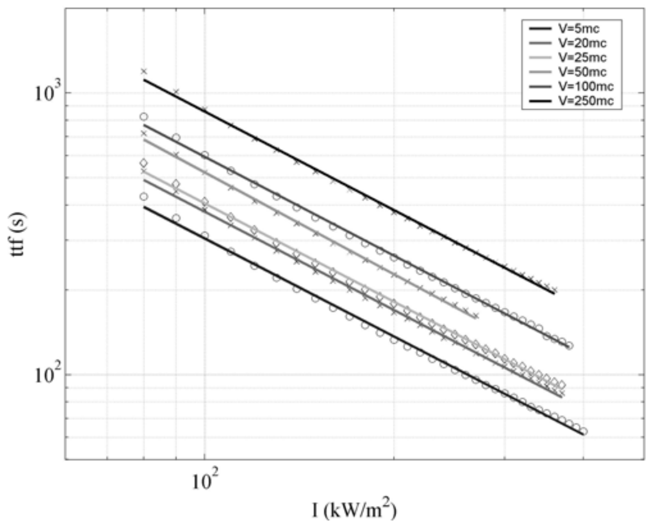


Figure 8: Times to failure obtained for horizontal cylindrical pressurised vessels with length/diameter ratio equal to 1.8. Failure with open PRV under distant source radiation

Figure 7 shows the data matrix obtained for pressurized vessels. Figure 8 shows the data matrix obtained for horizontal cylindrical pressurised vessels with length/diameter ratio equal to 1.8. As discussed above, the data in figures 7 and 8 may be directly used to estimate the time to failure for the specific vessel of interest. An example of the correlations between the ttf and the radiation intensity obtained by this approach for selected geometries are shown in table 2.

3.3 Envelope correlations for storage safety assessment

If no precise data are immediately available for the vessel geometry, a straightforward approach to ttf and storage safety estimation useful for emergency management may be obtained from the approach developed. Figures 9 and 10 show the envelope correlations obtained respectively for horizontal and vertical pressurized vessels under distant source conditions.

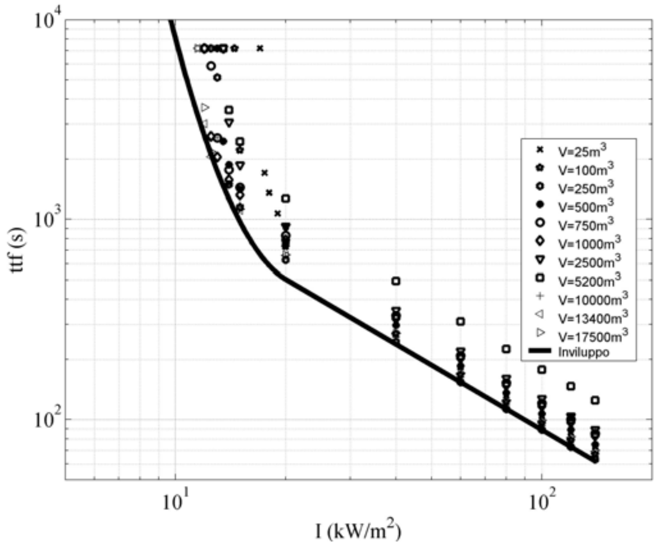


Figure 9: Envelope of times to failure obtained for vertical cylindrical atmospheric vessels under distant source radiation

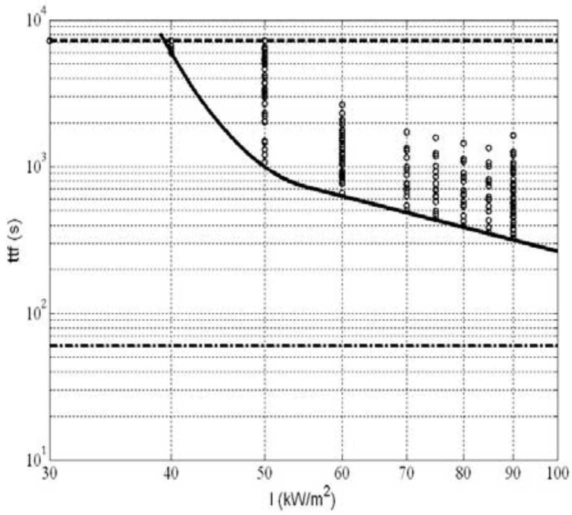


Figure 10: Envelope of times to failure obtained for horizontal cylindrical pressurized vessels (1.5 to 2.5 MPa design pressure) under distant source radiation

The envelope correlations shown in figures 9 and 10 define the minimum credible time to failure for vessels exposed to fire. Thus, if the time to failure is compared to a maximum time required for effective mitigation, the threshold values of stationary radiation required for credible escalation may be identified. Table 3 reports the threshold values and the safety distances estimated by this approach [8].

Table 2: Envelope correlations for distant source radiation.

Equipment	Envelope correlation
atmospheric	ln(ttf)=1.13·ln(I)–2.67·105 V + 9.9
pressurized	ln(ttf) = 0.95·ln(I) + 8.845 V + 0.032

Table 3: Safety distances for escalation caused by fires

Scenario	Target	Threshold (kW/m^2) ttf 10 min	Threshold (kW/m^2) ttf 30 min	Safety distance
fireball	atmospheric	15	10	25m from fireball border
	pressurized	---	---	not credible
jetfire	atmospheric	15	10	50m from flame envelope
	pressurized	60	40	25m from flame envelope
pool fire	atmospheric	15	10	50m from pool border
	pressurized	60	40	15m from pool border

4.0 PASSIVE PROTECTION OF PRESSURIZED STORAGES

The correlations and the data reported above are conservative and do not take into account the protection systems of the storage vessels. Even if active systems have an important role in emergency management, active protections, although compulsory, have a limited reliability due to delayed activation, possible damage in the primary event, possible failures of critical components. Therefore, passive protection of pressurized storage tanks is normally adopted to mitigate the effects of external fires. It is thus important to take into account the role of passive protections in the determination of vessel time to failure.

A preliminary analysis of the influence of the thermal insulation layer, performed assuming full engulfment conditions of pressurised vessels, evidenced that the time to failure of insulated vessels (ttf_{pv}) could be obtained simply adding the time to failure of the insulation layer (tt_{pl}) and the time to failure of the uninsulated vessel (ttf_{np}):

$$ttf_{pv} = ttf_{np} + ttf_{pl} \quad (2)$$

Thus, a protection layer on the vessel results in a further term that adds to the unprotected vessel ttf. Analysing the influence of the type of insulation material on the ttf_{pl}, it was possible to observe that this is dependent from several parameters: density; thermal conductivity; heat capacity; and limit temperature.

The limit temperature of a thermal insulation material is the temperature above which the material looses its structural integrity and insulating properties. Thus, the ttf_{pl} should be considered actually as the elapsed time from the fire start to the thermal insulation layer. The importance of this parameter is evidenced in table 4, that compares the results obtained for a vessel under fire conditions considering different insulation materials. As shown in the table, above 70kW/m^2 of radiation intensity, the limit temperature of glass wool is rapidly exceeded, thus the passive protection scarcely influences the overall ttf of the vessel. Even if these results may be in part caused by the very conservative assumptions introduced (no passive protection above the limit temperature), it is clear that the parameters of the thermal insulation greatly influence the effectiveness of the passive protection layer.

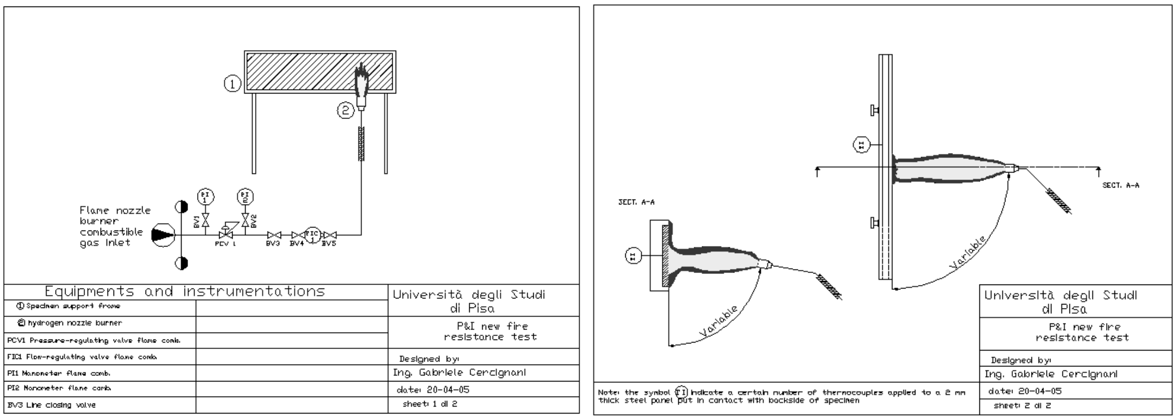
5.0 EXPERIMENTAL TESTING OF MATERIALS FOR HYDROGEN STORAGE VESSELS PASSIVE PROTECTION

The utmost importance of a thorough characterization of the relevant properties of passive protection materials, joined to the peculiar characteristic of hydrogen jet fires requires a specific testing in order to fully understand the adequacy of materials for the protection of hydrogen tanks. Moreover, the reliable modeling of the time to failure and the validation of the modeling approach developed, described above, requires the availability of robust experimental data to extrapolate the parameters of the protection material. A further requirement for experimental trials is that new advanced composite materials were proposed for the protection of hydrogen storages.

Table 4: time to failure of a 50m^3 vessel (design pressure of 1.5MPa) calculated for a 20mm layer of passive protection materials

Thermal insulation data		**no**	**Glass wool**	**Stone wool**
Thickness		---	20	20
Thermal conductivity mW/(m K)		---	30	33
Heat Capacity (kJ/kg K)		---	1	1
Maximum working temperature (K)		---	773	1123
Time to failure (s)				
Radiation intensity (kW/m^2)	60	924	> 7200	> 7200
	70	704	2978	> 7200
	80	556	570	> 7200
	90	452	466	> 7200
	engulfment (170)	202	205	> 7200

Therefore, a specific experimental device was realized to provide the parameters necessary to model the passive protection material and to test its adequacy under hydrogen jet fire conditions. The experimental set-up is shown in figure 11. The bearing structure, that must support the specimen, and the size of the specimen (155 x 800 mm), that must be subjected to the action of flame, were maintained equal to those suggested by international standards UNI 9174-9174/A1 and ASTM E 1321-93. The main modification with respect to the standard apparatus consists in not using the radiant panel as heating system, so that its bearing structure and its feeding system are no more necessary. The heating source is the direct flame produced by a nozzle burner for hydrogen. This allows a more realistic simulation of jet fire impingement.



a) b)

Figure 11. P&I (a) and equipment orientation (b) of the experimental device for the testing of passive protection materials.

This nozzle burner produces a diffusion flame with a length included between 300 mm and 800 mm and with maximum diameter of 70 mm. It is mounted on a bearing structure that allows the variation in all directions of the flame/sample impact angle. Therefore the nozzle burner is supplied with a combustible gas feeding line, covered with insulation material to protect it by heating. The gas feeding line is constituted by: a hydrogen cylinder (hydrogen), a pressure-regulating valve with two manometers to control pressure upstream and downstream the pressure-regulating valve, a valve to close the line, tube and flow regulator chosen according to exercise conditions and flow rate of hydrogen.

The instrumentations, used to collect data useful to understand the behaviour of tested materials, are: an infrared video camera, that allow the control of constant temperature of sample surface, impinged by the flame; a certain number of thermocouples type K (Chromel/Alumen) fixed to a 2 mm thick steel panel, put in contact with the backside of specimen and used to analyse the variations of time/temperature on the specimen; a data acquisition system (data logger) with analogical and digital signal ports to interface thermocouples with a computer and a video board to acquire images provided by a video camera (see figure 12).

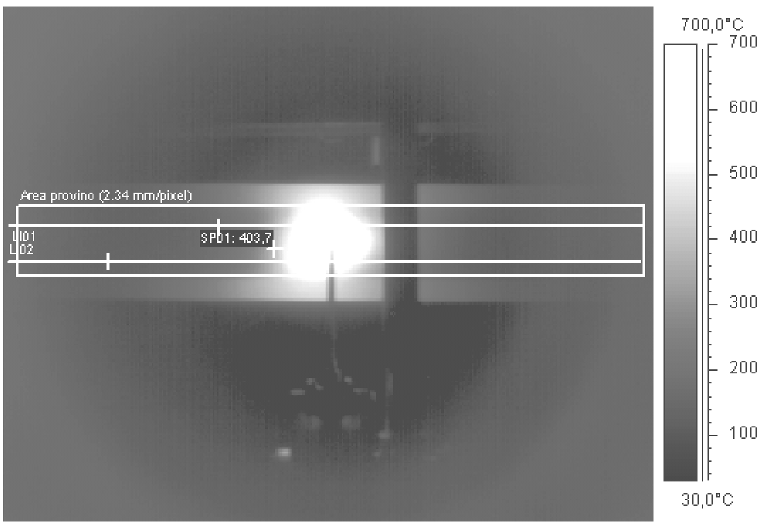


Figure 12. Example of and infrared image taken on the panel video camera.

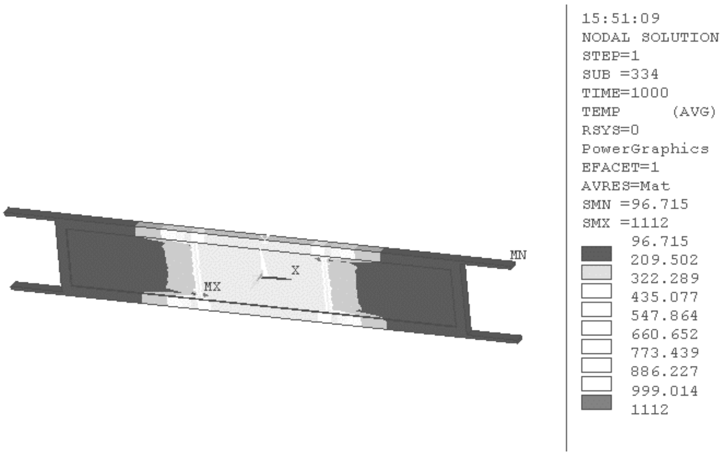


Figure 13. Simulation of the experimental test of a composite protection material under a hydrogen jet flame

In order to reproduce the experiment and to test the extrapolated values of the parameters of the protection materials, a finite element simulation of the panel was performed using the Ansys code. The panel preliminary study allowed to set up and conduct the experiment obtaining significant results, identifying the more critical zones for thermal degradation and hot spots. The model can predict the thermal history of the panel showing a dynamic temperature profile: in this way suggestions for the thermocouple setting and a isothermal map to match with the thermocamera outputs were obtained. Simulations were performed considering a not specified radiating source as thermal input in order to focus on the conductive-radiative behaviour of the panel. The main assumption was to consider only one surface irradiated and a convective dispersion from the other ones, using both uniform and concentrated sources of radiation. The panel was modelled considering the resin-fiber composite boxed up in a L-shaped metal support in order to match the different thermal behaviour of the two components. Significant qualitative results were obtained, as shown in figure 13.

The modeling approach developed to analyze the experimental data allowed the extrapolation of the main parameters of the passive protection materials (density, thermal conductivity, heat capacity, limit temperature) and their validation by the simulation of experimental runs. The qualification of passive protection materials for hydrogen storages was possible by this approach. The results of the experimental runs were used for the estimate of the overall ttf of pressurized hydrogen storage vessels, and in particular to test the effectiveness of new composite materials based on basalt fibers.

6.0 CONCLUSIONS

A simplified approach was developed for the management of hazard due to external fires involving hydrogen storage vessels. The approach was based on the development of tools for the straightforward assessment of vessel time to failure due to fire radiation in different radiation modes. The estimation of the vessel time to failure allowed the evaluation of the time available for effective mitigation actions and the timing of emergency response. The approach was extended to include the effect of passive protection. The results evidenced that specific and reliable values are needed for the parameters that characterize the performance of the passive protection systems, in particular under the conditions of hydrogen jet-fire impingement. A specific experimental set-up was developed to provide these values and to qualify advanced materials for the protection of pressurized hydrogen storage vessels.

ACKNOWLEDGMENTS

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