Design of a Rescue Vehicle for Hazardous Industrial Environments

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The manuscript describes the problems raised by the design procedure of a rescue vehicle for hazardous environments within an industrial facility. Specifically, the paper focuses on the pre treatment processes of crude oils characterized by high concentrations of toxic and hazardous substances, primarily hydrogen sulphide. The project manager, appointed for designing the desulphurization plant, has to provide feasible and effective solutions in case of accident (*i.e.* emergency preparedness and response). Actually, the accidents that may occur in a desulphurization process are explosion, fire, and toxic release. In particular, the designer has to suggest a suitable typology of emergency vehicle to rescue the field operators as well as injured people. These points are quite specific and do not pertain to the common technical background of engineers. The manuscript describes how we addressed the main qualitative and quantitative points that condition the selection and design of an emergency vehicle.

1. Introduction

The literature is rather poor of papers on design issues and construction directives for emergency and rescue vehicles. Most of the manuscripts are devoted to tunnel safety and specifically to fire risk (AFAC, 2001; NFAAA, 2004; Beard, 2005; Miclea *et al.*, 2007; Tie-Nan and Zhi-Min, 2007) whilst a more general organization is given by Bajpai and Gupta, 2005.

The manuscript discusses the selection and design of a transport system for passengers and light equipment for an onshore crude oil extraction plant. Specifically, the transport system operates in the crude oil pretreatment section (*i.e.* the desulphurization plant). The reader will discover how the potential dispersion of hydrogen sulfide increases significantly the precautions the designer has to account for, not only in terms of operators' safety but also for explosion risk and engine integrity. The transport system should provide an efficient, safe, reliable, and robust protection to the personnel moving within the industrial site during the execution of their tasks and should achieve a prompt emergency response (*i.e.* evacuation and rescue).

This paper proposes a transport system that is protected against the following:

- hazardous and toxic gases release;
- fire radiation;
- overpressure blast;
- extreme harsh weather conditions.

Usually, the vehicles for the personnel moving, under routine operation, have to be switched off in case of emergency to avoid being a trigger for further hazards. Conversely, a vehicle specifically designed for the evacuation and rescue of field operators must go on operating when an emergency occurs, while coping with the extreme conditions of the envisaged environment.
The design team proposed a vehicle that should guarantee both the workforce and equipment transport services under the following meteorological conditions (based on a return period of 100 years):

- very cold winters and very hot summers. The extreme temperatures are between 40 °C and +45 °C;
- maximum hourly wind speeds are 25-30 m/s with gusts up to 35 m/s;
- relative humidity values are min. 6%, max. 100%;
- rainfall intensities of 356 mm/h for 1 minute of deluge, 89 mm/h for 10 minutes;
- maximum thickness of snow/ice cover: 40 cm.

The plant dimensions are noteworthy, being some hundreds of meters in length and width. The plant has an internal road network with several crossroads. This road network allows the emergency vehicle reaching the most important blocks of the plant. Nonetheless, to approach a single process unit it is necessary to walk along specific pavements. The whole plant perimeter is fenced and one road runs along it to be used as the evacuation route.
It is possible to single out three zones of the plant for the toxic risk classification: high, medium, and low risk. In the high-risk zone, the operators wear continuously a breathing apparatus (BA) and work under enhanced safety procedures. No specific transport system is required inside these areas since they are a few, small, and clearly identified. The medium risk zone is the largest of the whole plant. The operators do not wear any BAs but BAs must be available. A specific transport system is required inside this area. Finally, the low risk zone does not require any toxic gas protections and its area is even smaller than the high-risk zone.
In case of accident (*i.e.* emergency condition), the personnel outside of the protected facilities will don their individual BAs, abandon the affected area, and proceed to the nearest available muster point (MP). MPs are designed to provide sufficient endurance and maximum manning capacity. Personnel stay there until the end of the emergency or further evacuation is supplied. MPs are designed along the boundary evacuation road as well as inside the plant in order to reduce the workforce escape routes by foot according to BAs capacity.

2. Vehicle typology

This manuscript focuses only on the design of a vehicle typology for emergency response, *i.e.* capable of operating in flammable hydrocarbon/toxic gas clouds with smoke presence and low visibility (<10m); of withstanding 0.1 bar blast overpressures (pulse duration: 200-300 ms); of resisting to a radiative heat flux of 9 kW/m2 for a duration of 30 minutes.
The harsh conditions to be coped with (*i.e.* blast overpressure, heat radiation, flammable atmosphere, etc.) may give rise to dangerous consequences (*i.e.* vehicle turnover, lateral

shift, chassis rupture, auto-ignition, etc.). Figure 1 shows the main accidental and environmental dangerous scenarios for the vehicle and the primary possible consequences/outcomes.

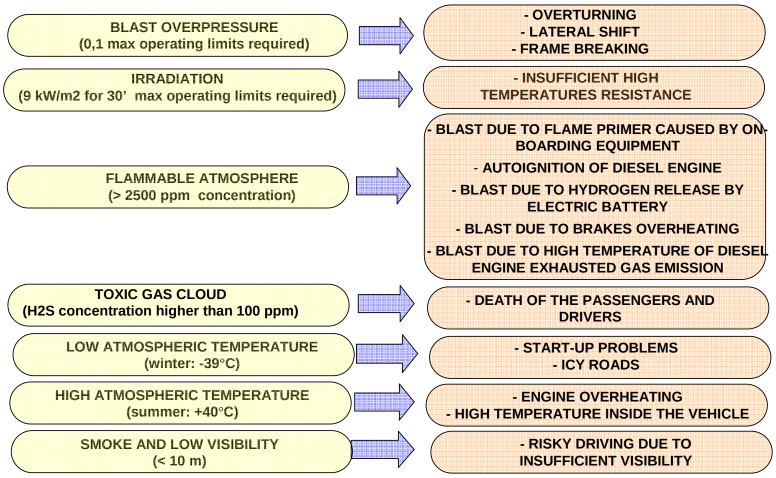

Figure 1: Accidental/environmental dangerous scenarios and possible consequences

The working environment of the crude oil pretreatment plant is exceptionally harsh and potentially aggressive. As a result, the market does not currently offer any suitable vehicles for this environment.

One of the most challenging accidental scenarios is the gas release event. Specifically, we are speaking of a natural gas dispersion characterized by high concentrations of hydrogen sulfide. Besides the toxicological concern of this mixture, one possible outcome is the autoignition of hydrogen sulfide inside an internal-combustion engine. As discussed in Tyrer (1980), Chaplin (1987), Phillips (1987), and Pritchard and Taylor (1987), hydrocarbon gas clouds with hydrogen sulfide concentrations as low as 2-5% volumetric can bring to engine malfunction and eventually to dangerous explosions (the flammable gas touches the hot surfaces of the engine). Usually, a few thousand ppm of H_2S increase the engine speed. If the engine runs at a higher regime, then it increases the contaminated air intake. A synergistic phenomenon may occur up to a rotating speed and an H_2S threshold that set off a sudden burst of the engine. To get round this problem, it is possible either to select alternative solutions to the internal-combustion engine or to work with bottled air as the comburent of the combustion reaction with fuel that occurs inside the engine.

With reference to the possible solutions for the emergency vehicle engine, we have:

- electrical engine with batteries;
- electrical engine with fuel cells;
- compressed air engine;
- internal-combustion engine with filters;
- internal-combustion engine with bottled air;
- hybrid solution (diesel + electrical engine).

The hypothesis of electrical engine with batteries was discarded due to the overall high weight/power ratio, the rather low autonomy, the battery life and recharging time, the investment cost, the required maintenance, and finally the operating temperature range of the engine (usually between -20 °C and + 65 °C).

The electrical engine with fuel cells solution was rejected due to: the presence of hydrogen as propellant (*i.e.* high pressure storage, high explosivity), the limited number of vehicles operating as public buses in industrialized countries, the oxygen coming from external air (possibly contaminated).

The compressed air engine was abandoned since it is still under development. At present, there are not any heavy working vehicles (*e.g.* there are only some prototypes with reduced autonomy and 2-4 passengers).

The filters adoption for the internal-combustion engine is a rather peculiar solution. NBC (Nuclear Bacteriological Chemical) filtering units are used in army applications to protect closed environments (buildings, armored vehicles, and naval installations) of sensitive or valuable pieces of hardware by preventing the intake of NBC agents and supplying purified air. These devices consist of filters, which trap the particulate in the air, and of chemical absorbers, which retain the toxic gases by means of physical absorption or chemical reaction. The life of a charcoal chemical absorber depends on its saturation, which causes loss of efficiency, and according to the number and typology of absorbed toxic gases, concentration, temperature, and air humidity. Our preliminary research showed that NBC filtering units are not applied to avoid the external air intake by internal-combustion engines, but are adopted only to protect soldiers.

Table 1: Evaluation of the engine alternatives with corresponding pros and cons

ENGINE ALTERNATIVES	SAFETY	RELIABILITY	EFFICIENCY	REFERENCE	COMFORT	ECONOMY
Electrical engine with battery	High	Low	Medium	High	High	Medium
Electrical engine with fuel cell	Low	Low	Medium	Low	High	Low
Compressed air engine	High	Medium	Low	Low	Medium	Low
Diesel with stored air	High	High	High	High	Medium	High
Diesel with special air filters	Medium	High	High	Low	Medium	Medium
Hybrid type: diesel + electr.engine	High	Medium	Medium	High	High	Low

Conversely, a number of evacuation and rescue vehicles adopted the bottled air solution. The rescue vehicles for long road tunnels (e.g. Frejus tunnel and Mont Blanc tunnel) are some examples where the compressed air storage as comburent of the motor engine is chosen to withstand a high concentration of combustion gases (e.g. CO2, CO, H2O, soot) in case of fire. Bottled air is also a proper solution for the personnel breathing apparatuses.

Finally, the hybrid alternative (internal-combustion engine + electric engine) was discarded due to the same reasons reported for the electric engine solution. Table 1 reports a summary of the pros and cons of the engine alternatives here discussed.

3. Vehicle traction

The further step for the selection of the emergency vehicle is the traction system. We have the following alternatives:

- tires;
- metal tracks;

- metal anti-spark tracks with a rubber belt.

The tires alternative, coupled to a four wheels drive, is the most common and efficient in terms of maximum speed and maneuverability but it is hard to drive over obstacles and has a reduced resistance to high temperatures. The metal track is by far the most robust solution but at the same time is also the less efficient and may generate sparks.

A third hypothesis is a tracked vehicle with an anti-spark solution (*i.e.* a rubber belt over the tracks). The adoption of rubber (either for the tires or for the cover of the metal tracks) is subject to the temperature reached by the asphalt road in case of fire. As aforementioned, the vehicle is designed to withstand a radiative heat flux of 9 kW/m^2 for 30 min. This design specification is also extended to the surrounding environment. This means that we evaluated the maximum temperature reached by an asphalt road exposed to such a heat flux. We had to understand if the asphalt melts and finally compromises the structural integrity of a tubeless tire or of the rubber belt covering the metal track. The alternative between tires and metal tracks plays also a role on the stability of the vehicle in case of overpressure blast.

Figure 2: Layout of the temperatures for the simulation of the tire heating by the radiative flux

4. Tire dynamics in case of fire

To understand what happens to a tire exposed for 30 min to a radiative heat flux of 9 kW/m^2 we developed a first principles model comprising an overall energy balance. The mathematical model is based on a differential-algebraic equations system (DAE) where we assume the heat flux continuity between the internal/external and front/rear surfaces of the wheel with an energy store for the pressurized air inside the tire.

As a result, we write four algebraic equations for the continuity of the convective and conductive heat fluxes for the unknowns T_1, T_2, T_4, T_5 (see Figure 2) coupled to an ordinary differential equation that describes the T_3 dynamics (we assume perfectly mixed conditions inside the tire). The convective terms are associated both to the heat exchanged between the external surfaces of the tire and the ambient air, and to the heat exchanged between the internal surfaces of the tire and the pressurized air. The conductive terms describe the heat flux inside the rubber shoulders. The resulting DAE system is based on a rather simplified hypothesis, since it assumes a prompt response of the tire shoulders. Under real conditions, the rubber portion of the tire stores heat with a more sluggish response respect to the ideal model based on the continuity of heat fluxes (the results are shown in Figure 3 and Figure 4).

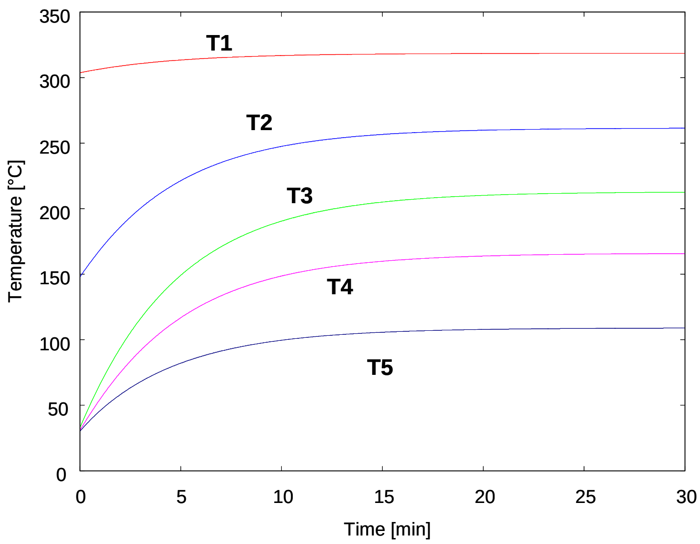

Figure 3: Temperatures evolution of the tire shoulders and of the internal air

Nonetheless, for design purposes, the aforementioned DAE system is a proper choice since it is conservative and shows how in less than 10 min the tire reaches a steady state condition (especially for the exposed shoulder, *i.e.* T_1).

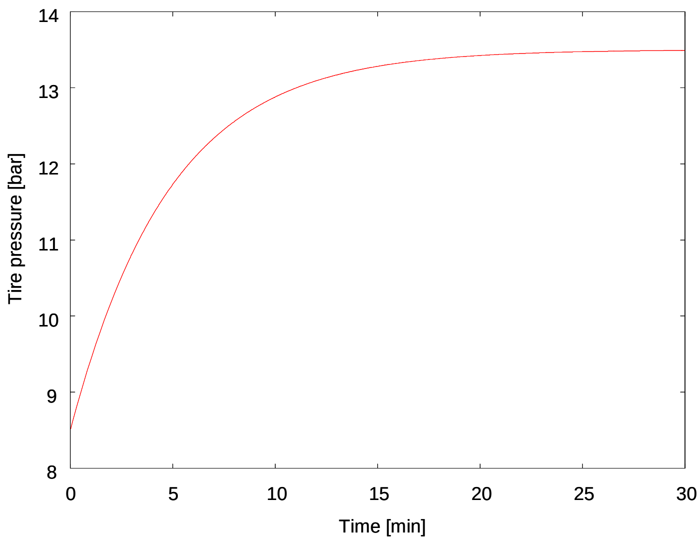

Figure 4: Tire pressure dynamics (initial inflate pressure is 8.5 bar)

This means that the final values predicted after an irradiation of 30 min are equal to those computed by a more detailed and realistic model.
With reference to Figure 4, we observe an internal pressure increase of about 5 bar that coupled to a maximum shoulder temperature of about 320 °C would compromise the structural integrity of the tire and would drive either to explosion or rubber melting and combustion. These issues drove us to design a metallic and partially reflective shield to be set in front of the tire like a wheel cover.
The analytic solution (Incropera and De Witt, 2006) of a partial derivative equation, describing the transient of the heat conduction inside a semi-infinite plane with constant boundary conditions (*i.e.* the radiative heat flux and an asymptotic value for the bulk temperature of the ground), allowed determining the temperature reached by the asphalt after a radiation of half an hour.
Our simulations determined surface values of about 150-180 °C that start melting the asphalt. Nonetheless, a specific rubber tire capable of withstanding severe operating conditions with a reflecting and isolating lateral wheel cover looks to be a suitable solution for the vehicle traction.

5. Vehicle resistance to explosions

The vehicle was also designed to withstand a blast overpressure of 0.1 bar with a pulse duration: 200-300 ms. Besides the structural resistance of the rescue vehicle to an explosion, the design activity focused on the overturning assessment as well as the quantification of dangerous lateral shifts. We assumed a maximum lateral displacement (produced by the blast overpressure) of 0.4 m. A simple mechanical torque balance, based on Figure 5, allowed determining the vehicle weight, the barycentre position, the axial width, and the maximum height.
The higher friction coefficient exerted by the tracks respect to the tires solution makes the former hypothesis more stable than the latter. Nonetheless, the tires solution is still feasible and allows producing a vehicle that is quicker and easier to control.

6. Concluding remarks

The final configuration adopted for the emergency and rescue vehicle was a bus-like option that allows carrying more than 20 passengers. The diesel engine works with ambient air under normal conditions but switches to bottled air when the hydrocarbon/toxic gas concentration exceeds a predefined threshold, which is measured by a gas detector.
The traction system is based on four-wheel drive with all-terrain tires, which are suitable to operate on snowy and icy roads. The bottled air is also used (once laminated, preheated, and humidified to reasonable values) by the cabin passengers. A further energy balance on the cabin allowed designing the air conditioner. To keep as low as possible the external temperature of the vehicle we specified a fire resistant and highly reflective paint, a water spraying system to quench the vehicle body (this solution is widely adopted for the rescue trucks in road tunnels), and a reflecting windshield (to lower the radiation directly transmitted to the driver). Finally, a thermographic camera

(working in the infrared spectrum) assists the driver when smoky environments lower the visibility.

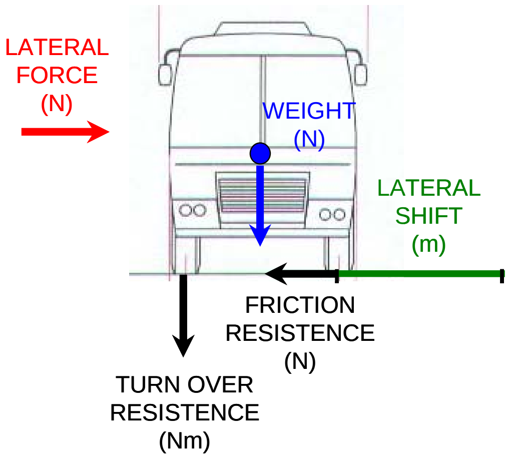

Figure 5: Torque balance for the overturning and the later displacement evaluation

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