AVIATION FUEL STOREHOUSE FIRE MODELLING FOR EMERGENCY PLANNING PURPOSES

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As a potential source of a major accident, aviation fuel tanks represent a potential source of danger not only for the airport but also for businesses in the vicinity of the airport. Fire is one of the main hazards associated with the operation of fuel storage tanks. Depending on the type of storage tanks, there may be a fire in the tank itself or a fire in the bund. An important factor in an actual fire is the influence of wind, which affects the geometry of the flame and thus the range of heat flux and its impact on other equipment in the vicinity of the fire. Another phenomenon known to occur in industrial fire accidents is the domino effect, where the fire can spread to other equipment and cause more severe damage. From this point of view, a systematic risk analysis is needed, where the procedures known within the SEVESO series of directives can be used. The outputs of the risk analysis and impact calculations of the consequences allow better planning for an effective and safe management of the accident. This article describes the possible consequences of an aviation fuel storage accident at an airport near which manufacturing plants and other infrastructure are located.

KEYWORDS

Aviation fuel, modelling, emergency planning

1 INTRODUCTION

Documented storage tank fires in industry [Zheng, Chen 2011] show that the error that led to the accident occurred mostly during maintenance, repair, and loading or unloading. Nearly one-third of the accidents were caused by human errors in operation, including maintenance. According to [Chang, Lin 2006] 85% of accidents are fire and explosion. 80 accidents (33%) were caused by lightning and 72 (30%) were caused by human errors including poor operations and maintenance. Fuel storage tank fires are a relatively rare accident, but can lead to serious consequences for the facility, the environment, and the health of workers and adjacent businesses [Nivolianitou et al. 2012]. A high number of deaths are caused by the toxicity of smoke particles and gases from the fire. The issue of carbon monoxide and soot formation in fires has been extensively studied and important results described by [Gottuk 1992]. Computational models provide an indication of the hazard zones after the release and dispersion of hazardous substances in densely populated areas. Nevertheless, the identification of hazard zones is important to evaluate the potential consequences of major accidents or terrorist attacks [Bernatik et al. 2008]. Table 1 [Environmental Assessment Services for Permanent Aviation Fuel Facility Environmental Impact Assessment Report 2007] lists some of the accidents of storage tanks containing aviation fuel.

Incident	Brief Description
Ajjacio, Corsica, 1970	Two tanks containing one million litres of kerosene exploded causing US$300,000 damage.
Netherlands,1975	A metal storage tank of 5000m3 capacity encased in concrete and covered with earth, 1/3rd full of aviation fuel exploded when lightning stuck a tree adjacent to the tank. The tank allowed to burn out.
Yokohama, Japan, 1981	An explosion in an underground storage tank containing jet fuel. Nearby residents were evacuated and there were 2 injuries.
US, 1985	A 40 m diameter aviation fuel tank ignited when fire fighting foam was applied.
Baltimore airport, US, 1989	Jet fuel overflowed a storage tank due to a defective bleed valve.
Dikson, Russia, 1995	Pipeline ruptured at storage tank under weight of snow at airport. 1800 tonnes of jet fuel poured over snow and ice and then to sea.
Trainer, US, 1998	A 55-foot tank containing 16,000 bbl jet fuel exploded and burned at a refinery. Approximately 700,000 gallons of fuel burned for more than four hours before being brought under control. No death or serious injury.
Anchorage, Alaska, US, 2000	A fire occurred on a tank during tank cleaning. The tank contained 2000 gallons of jet fuel. No injuries.

Table 1. Accidents of storage tanks containing aviation fuel

These accidents demonstrate not only the widespread destruction of the surrounding area along with the potential environmental consequences, but also the need to prevent similar accidents [Woodward, Pitblado 2010]. Different models available in the literature for calculating thermal radiation indicate different safe distances that need to be maintained to avoid a domino effect from a pool fire. The calculation of thermal radiation reaching a target, based on a visibility factor multiplied by blackbody radiation, was first used by [Sullivan et al. 2003] to model radiation from a bushfire. This methodology for calculating radiation flux from a pool fire was later used by [Zarate et al. 2008] to determine safe distances for different scenarios based on a critical value of radiation heat flux. Subsequently, CFD calculations of the temperature profiles for different sizes of pool fire were also performed. These results are then coupled with modified radiative models to obtain safe distances from different pool fire variants [Lam et al. 2015, Sudheer et al. 2013].

2 STORAGE TANK FIRE

The worst fire scenario is considered to be a fire of both the storage tank and the bund at the same time when the largest area is on fire. Fuel storage tank emergencies can present several alternatives such as pool fire - heat flux, pool fire - toxic dispersion of combustion products, flash fire and vapor cloud explosion. In the pool fire calculations, heat flux boundaries are considered for surrounding objects as well as responding personnel. The effect of thermal radiation depends on the length of exposure and the level of thermal radiation. Smoke caused by the fire can cause visibility problems for the control tower as well as aircraft, and toxic fumes from the smoke can endanger the health of personnel in nearby operations or infrastructure - roads, railways and air routes.

The graphical representation using available map data with the display of the range of heat flux with different intensities provides the necessary information for the intervening forces as well as for the commander of the intervention for a safe intervention.

In the next part of the paper the results of calculations of JET - A1 aviation fuel storage tanks fire at the selected airport in the vicinity of which manufacturing enterprises are located are presented.

The heat flux density was calculated for a storage tank fire with an area of 513m^2 and a total aviation fuel capacity of 600m^3 Fig.1.

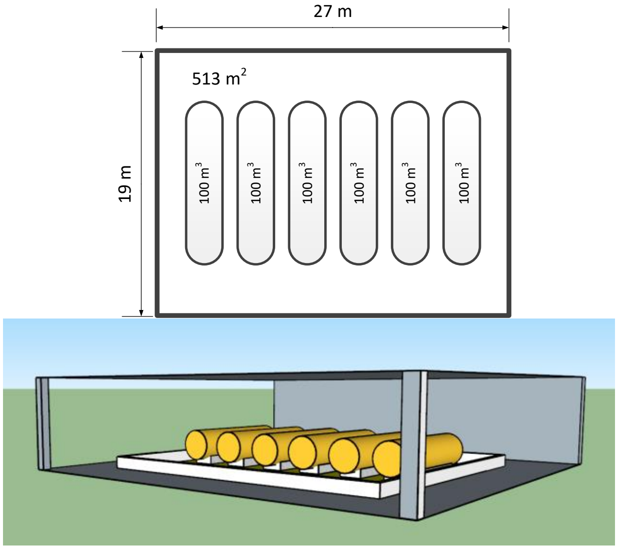


Figure 1. Schematic diagram of storage tanks

The calculations consider the limits of the heat fluxes for the surrounding technology as well as for the intervening personnel in case of fire (limits from 44 kWm^{-2} up to 1.8 kWm^{-2}). The size of the storage tank area for each scenario has been rounded up.

Boiling point [°C]	> 90	165 for calc.
Flash point [°C]	38 - 66	
Heat of combustion kJ/kg	42709 -42757	43160 for calc.
GHS fire hazard class	3	Flam. Liq.3 - H226
Lower and upper explosive limit [% v/v]	0.6 - 8	
Saturation vapour pressure according to REid [kPa]	1-25 kPa at 37.8 °C	
Relative density 15 °C	0.75 -0.86	0.804 for calc.
Solubility in water	insoluble	

Table 2. Physicochemical properties of jet fuel Jet A/A1

Pool fire is assessed if the following conditions are met:

- the substance belongs to the hazard categories of flammable, highly flammable or extremely flammable liquid,
- the duration of the fire is at least 15 minutes [Kandráč et al. 2001].

With an area burning rate of 0.039 kg.m^2.s^{-1} and a corresponding area over which the oil can be spilled in space, the above conditions are already met for the amount released in a continuous spill of 10 minutes. The bounded pool fire model presented in [CPR 14E 2005] was used to calculate the heat flux.

3 DESCRIPTION OF CONDITIONS

Considering the technology used, the most likely type of fire is a pool fire where we can define two types of spills according to CPR 14E, namely:

- G1 - Immediate spill of the entire contents of one storage tank, pool fire with 1.5 times the footprint of the bund, receptor located at ground level
- G2 - Continuous spill of the entire contents of one storage tank within 10 minutes, pool fire with bund footprint, receptor located at ground level
- Weather Stability Class D5 - this weather stability class was chosen as this is an area where wind speeds are often high.

  The height of the catch basin edge is an important parameter for the calculation of the fire area. In the case of an immediate release of the entire contents of one tank, the fire area is 1.5 x the bund area.
- For a continuous release, the actual surface area of the bund must be entered, for an instantaneous release of the entire contents of the bund, 1.5 times the surface area of the bund is entered because splashing over the edge of the bund is assumed [BEVI].

INPUT DATA				
Parameter	**Symbol**	**Unit**	**Value G1 scenario**	**Value G2 scenario**
SUBSTANCE				
Name of substance	-	-	Jet A1	
Density	ρ_l	kg.m^{-3}	804.00	
Mass Burning Rate	m_∞''	kg.m^{-2}.s^{-1}	0.0390	
Boiling temperature	T_b	° C	165	
Heat of combustion	ΔH_c	J.kg^{-1}	4.316E+07	
Flame radiation temperature	T_f	K	1 303	
CHARACTERISTICS OF DANGEROUS SUBSTANCE LEAKAGE				
Type of leakage	-	-	Instantaneous	Continuous
The border represents			Tank bund	
Volume of flammable substance	V	m^3	90.0	
Amount of flammable substance	m	kg	72 360.000	
Thickness	δ	m	-	

of the layer of flammable substance				
Ground plan shape of pool	-	-	Rectangle	
Length of sides 'a'	a	m	27.0	
Length of side 'b'	b	m	19.0	
Area of the tank bund ×1,5 (spill over bund system)/ Area of the bund system	S	m^2	769.50	513,00
Diameter of equivalent round pool calculated by area	-	-	S	
The receptor object level versus the pool level	z	m	0.0	
CLIMATIC CONDITIONS				
Ambient temperature	T_a	°C	15.00	
Relative humidity	RH	%	76.70	
Atmospheric pressure	P_{air}	Pa	101 325	
Wind speed	u_w	$m.s^{-1}$	5.0	
Gravitational acceleration	g	$m.s^{-2}$	9.81	
PARAMETERS FOR FIRE CALCULATION				
Ratio of flame surface covered with soot	ξ	-	0.80	
Fraction of heat radiated from flames surface (range 0,1 - 0,4)	F_s	-	0.300	

Table 3. Input data for pool fire calculation

The following table shows the resulting values of calculation of parameters of a pool fire.

OUTPUT DATA				
Parameter	**Symbol**	**Unit**	**Value G1 scenario**	**Value G2 scenario**
Fire characteristics:				
Amount of dangerous good needed for duration of 10 min fire	$m_{10\ min}$	kg	18 006	12 004
Duration of the fire	t_{max}	min	40.186	60.279
Diameter of equivalent circular pools	D	m	31.30	25.56
The average length of the flame	L	m	21.00	18.10
The angle of inclination of the flame	Θ	°	50.8	51.5
Average emitted heat flux from the source	E_a	$kW.m^{-2}$	43.4	42.4
Distances with upper heat flux levels for domino effect (from pool fire center):				
- 60 $kW.m^{-2}$	x_{60}	m	15.7	12.8
- 40 $kW.m^{-2}$	x_{40}	m	16.1	12.8
- 15 $kW.m^{-2}$	x_{15}	m	34.5	28.8
- 8 $kW.m^{-2}$	x_8	m	42.7	35.7
Impact to personnel:				
The distance from the center of the pool to the level of E=35 $kW.m^{-2}$	x_{35}	m	18.4	14.9
The distance from the center of the pool to the level of E = 19,46 $kW.m^{-2}$	$x_{19,5}$	m	30.7	25.5
The distance from the center of the pool to the level of E = 9,83 $kW.m^{-2}$	$x_{9,8}$	m	40.0	12.8
The distance from the center of the pool to the level of E=7 $kW.m^{-2}$	x_7	m	44.4	37.2
The distance from the center of the pool to the level of E=5 $kW.m^{-2}$	x_5	m	49.2	41.2
The distance from the center of the pool to the level of E=1,8 $kW.m^{-2}$	$x_{1,8}$	m	68.3	57.0

Table 4. Output data of pool fire calculation

In Table 5, the calculation of the range of heat flux intensity for different values of air humidity has been performed. These data must be taken into account when siting new buildings near fuel storage and, in the case of buildings in the danger zone, effective protection of these buildings must be designed according to the purpose. The worst-case scenario must always be taken into account, as the number of days with extremely high air temperatures is increasing in all locations in the world.

RH Heat flux	20%	40%	60%	80%	100%
	Heat flux range distance				
1.8 kW/m²	71.2	69.7	68.8	68.2	67.7
5 kW/m²	51.1	50.1	49.6	49.2	48.9
7 kW/m²	46.1	45.2	44.7	44.4	44.1
9.83 kW/m²	41.5	40.8	40.3	40	39.7
19.46 kW/m²	32.3	31.4	31	30.6	30.3
35 kW/m²	20.2	19.3	18.7	18.4	18.1

Table 5. Effect of atmospheric humidity on the heat flux range

4 THERMAL RADIATION

The effects of thermal radiation have physiological effects on the human body that can cause irreversible changes in the human body if exposure increases.

The body's ability to regulate temperature depends on its ability to get rid of excess heat derived from metabolism, a process dependent on ambient temperature and humidity. Short and long durations of high air temperature can cause thermal stress, which can have fatal consequences.

In the event of a fire, the air temperature may be too high, which in a person may manifest itself , as difficulty breathing leading to loss of coordination or high pulse, overheating of the body leading to collapse. The National Research Council of Canada (NRCC) fire tests indicate that an air temperature of 149°C is the maximum breathable air temperature that can be survived, even if only for a short period of time and with low humidity.

The maximum air temperature tolerance of the human respiratory system is approximately 203°C. In aircraft fires, passengers have been exposed to an upper limit of 309°C, causing third-degree burns within 20 seconds and making escape impossible. At temperatures above 150°C, pain due to skin burns occurs with exposure of less than 5 minutes. Difficulty in breathing occurs up to air temperatures of 140°C [Hadjisophocleous et al 1998, Bryan 1986].

When applying the probit function and an exposure time of 60 s, the lethal level of thermal radiation for both protected and unprotected persons is reached at 15 kW/m² (98% probability of death). A value of 5 kW/m² was chosen as the lower limit of the thermal radiation level for a given exposure duration of 60 s. The average probability of death for unprotected persons above 5 kW/m² is 50 %. In the 5 - 15 kW/m² band, a clothing correction factor of 0.14 is applied for unprotected persons. For persons protected by buildings, no fatal consequences to life are expected in this zone.

For the probability of death caused by thermal radiation, a probit function is valid according to the relation [Gottuk et al 1992]:

$$Pr = -36{,}38 + 2{,}56 \cdot \ln\left(t \cdot q^{4/3}\right) \tag{1}$$

Where:

Pr - probit value [-],

t - heat flux exposure time [s],

q - thermal radiation [W/m²].

The effect of thermal radiation is dependent on the duration of exposure and the level of thermal radiation. The duration of exposure in accordance with the CPR 18E procedure is 20 s. This standardised time has been chosen on the basis of the generally accepted assumption that persons will leave the exposed area within 20 s. For a given duration of exposure, the lethal level of thermal radiation for both protected and unprotected persons is a level of 35 kW/m² reached (probability of death > 98 %).

In contrast, the ARAMIS methodology considers exposure times of 30 and 60 s, respectively, and divides the effects into 4 levels, Table 6.

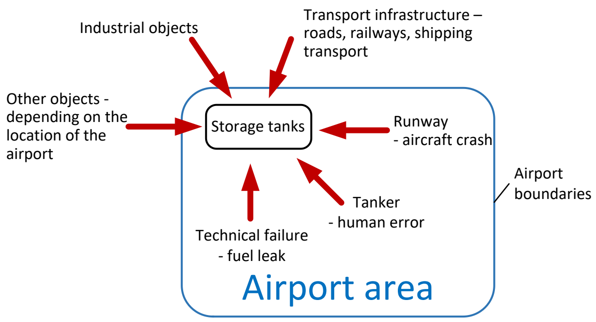
Rate of thermal radiation effect	*q* at exposition time of 60 s [kW.m²]	*q* at exposition time of 30 s [kW.m²]
1 – little or no effect	< 1.8	< 3
2 – reversible	1.8 – 3	3 – 5
3 – ireversible	3 – 5	5 – 9
4 – onset of lethality and/or domino effect	> 5	> 9

Table 6. Thermal radiation effect levels according to [ARAMIS 2004]

5 DOMINO EFFECT

A very serious phenomenon that occurs in storage tank accidents is the escalation of the accident to other facilities, technologies, buildings, etc. This phenomenon is called the domino effect. Current safety research has led to different methodologies to assess the significance of the domino effect at hazardous locations. Various direct and indirect mechanisms have been identified as relevant factors for domino effect escalation [Lee et al. 2004]. From experience, we know that the domino effect is caused by three main types of primary accidents, such as fire - flame (thermal effect), explosion - overpressure (pressure effect), explosion - flying objects (missile effect) or a combination of these. In the case of a pool fire, the domino effect manifests itself through heat flow. For the domino effect case, the optimal safe deployment of additional objects needs to be assessed to minimize the domino effect based on worst-case scenarios [Wo et al. 2011].

When analyzing and assessing the possible consequences in an on-airport and off-airport accident, it is necessary to consider how the fuel storehouse is endangered and in turn how the fuel storehouse endangers its surroundings and to perform a screening of the objects within the airport site and beyond the airport site boundaries, Fig. 2.



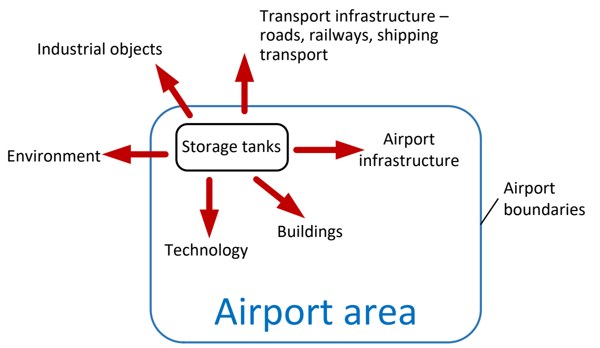


Figure 2. Types of hazards in storage tanks

This information provides a basis for assessing possible event scenarios in the event of a domino effect, not only for the primary event but also for possible subsequent secondary (BLEVE, Jet fire, VCE etc.) or tertiary events (damage of the surrounding units).

A possible procedure to achieve the optimal safe solution for the location of the aviation fuel storage is proposed in the algorithm in Fig. 3. The first step is to collect information about the storehouse such as physicochemical properties, volume, location, installed safety equipment etc. The screening of facilities and objects inside and outside the airport area is the input information in identifying hazards and vulnerable objects. This is followed by the analysis and calculation of possible emergency scenarios. Here it is possible to apply the ETA method - Event Tree Analysis. This is followed by a decision-making step and an assessment of whether a safe concept is applied to the storage tanks - safe distance, installed passive and active safety features and devices as well as organisational measures, Table 7. If not, the safe concept is applied to the storage units as well as other objects in the vicinity of the storage.

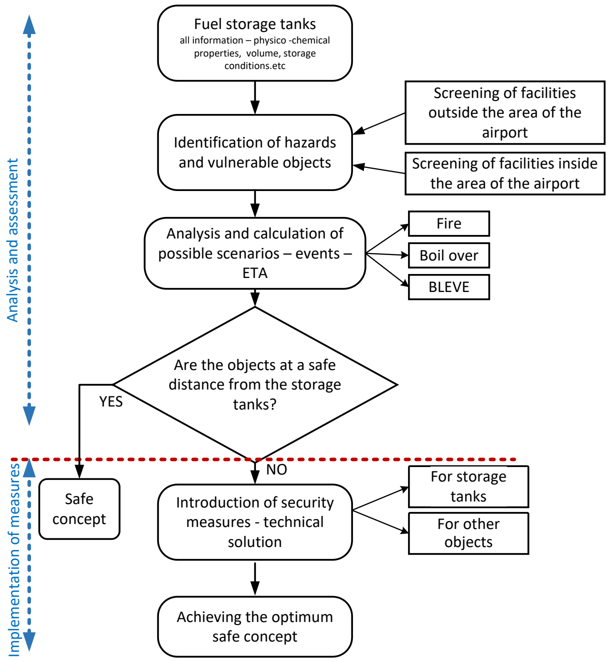


Figure 3. Algorithm for analysis and assessment of consequences and implementation of measures

How is the aviation fuel storehouse endangered?		
Hazard position	**Hazard source**	**Measures**
Outside the area of the airport	transport infrastructure - roads, rail, shipping transport	safe distance passive protection - earth bund active protection - fire extinguishing system
	industrial objects	
	other objects - depending on the location of the airport	
Inside the area of the airport	runway - aircraft crash	safe distance from the landing runway passive protection - earth bund active protection - fire extinguishing system
	Tanker - human error	technical - detection, fire extinguishing system, organisational - training, exercises
	Technical failure - fuel leak	inspection, maintenance, monitoring
What is endangered by the aviation fuel storehouse?		
Hazard position	**Hazard source**	**Measures**
Outside the area of the airport	transport infrastructure - roads, rail, shipping transport	safe distance passive protection - earth bund active protection - fire extinguishing system
	industrial objects	
	public objects	
	environment	monitoring
Inside the area of the airport	transport infrastructure of the airport	safe distance passive protection - earth bund active protection - fire extinguishing system
	buildings	
	technology	

Table 7. Implementation of measures for identified

Additional conductive cooling of the tank wall on the vapour side of the tank may be used by transferring heat from the tank wall to the liquid LPG to prevent the tank wall from heating above the critical temperature. This can be done by:

- Alloy mesh that is applied to the entire volume of the tank and distributes heat evenly to prevent overheating of the walls and temperature differences.
- Complete filling of the tank with porous alloy bulbs.

6 EMERGENCY PLANNING - IMPACT OF CONSEQUENCES

The role of the map documents in emergency planning as well as in response activities during an accident is to provide the necessary information, especially about the airport infrastructure and the wider surroundings. The graphical representation of heat flux values is only one of the parts that make up the map documentation for emergency planning.

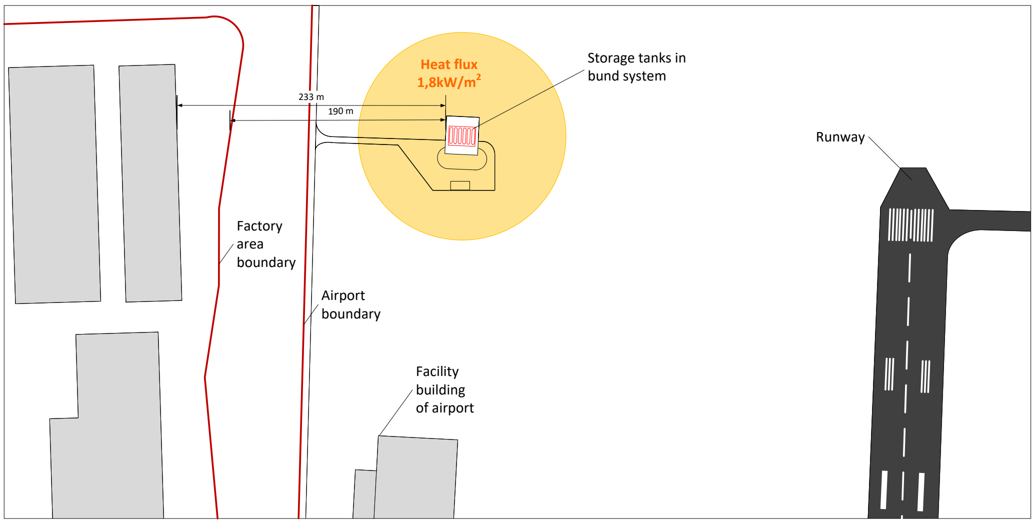


Figure 4. Schematic illustration of the heat flux range

The affected zone is marked as a circular area because of the possible change in wind direction due to the change in microclimatic conditions at the fire site. The model calculation was performed at one of the smaller airports with low aviation fuel storage capacity.

In the future, a switch to alternative fuels is also foreseen in air transport. One of these fuels is hydrogen, which has different physicochemical properties than the currently most widely used aviation fuel Jet A1. When storing hydrogen, the worst possibility of an accident is a hydrogen storage explosion. Hydrogen mixes with air more rapidly than aviation fuel vapour and spreads rapidly through the air, unlike aviation fuel, which forms a pool on the ground in the event of a leak. It burns with an almost invisible colourless, odourless flame, which is also an important safety concern.

Depending on the quantity and form stored - compressed or liquefied even the safe distances will depend on this technology.

Modelling the impact of the effects of potential negative scenarios and using these results for emergency planning purposes should be part of any operation where hazardous substances that may pose a risk to their surroundings are present.

Modelling of impact effects can be used not only for use in emergency planning but also in planning the location of other objects technology, roads, buildings etc.

Nowadays, using innovative information technologies such as augmented reality, it is possible to have a 3D representation of the heat flux impact for better visualization to the emergency responders and overall coordination of the intervention. With the help of GPS technology, the intervention commander can have an overview of each member's whereabouts and with the use of heads up technology, he can direct information to him immediately about the current situation or instructions for intervention.

7 CONCLUSIONS

Modelling the impacts of the effects of potential negative scenarios and using these results for emergency planning purposes should be part of any facility, including airports, as it can pose a significant risk with the potential to spread to its surroundings. With the use of modern technology we are increasing our preparedness to cope with these negative scenarios.

Impact modelling can be used not only for use in emergency planning but also when locating new operations or other infrastructure near airports or aviation fuel storehouses.

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