A PERFORMANCE-BASED FIRE HAZARD ANALYSIS OF A COMBUSTIBLE LIQUID STORAGE ROOM IN AN INDUSTRIAL FACILITY

Colleen A. Wade*
Building Research Association of New Zealand
Private Bag 50908 Porirua, New Zealand

Douglas J. Carpenter
Combustion Science & Engineering Inc.
Columbia, Maryland

ABSTRACT

This paper provides an example of the use of fire dynamics and engineering expressions in a performance-based fire hazard analysis of a combustible liquids storage room in an industrial facility. Such facilities, commonly built before the turn of the century in the USA do not meet present day fire codes, and the expense of altering the building to meet current codes can be prohibitively expensive. A performance-based hazard analysis has been carried out to identify the main risks and to specify appropriate fire protection measures commensurate with those risks. This example identifies fire scenarios and fire protection objectives and then uses fire dynamics and fire engineering relationships to estimate likely fire severity, heat release rates and suppression system response. Recommendations are made regarding both active and passive fire protection for the storage room.

INTRODUCTION

This paper presents an example of the use of performance-based design methods to determine appropriate fire protection for a combustible liquids storage room in an industrial facility. The project was carried out by the authors as part of a Masters level course in Industrial Fire Protection at Worcester Polytechnic Institute, USA.

The industrial facility accommodates a manufacturer of grinding wheels, a business with a turnover of about $US40 million per annum. The company produces many different kinds of abrasive wheels for applications ranging from grinding of windshields to hypodermic needles. Many different processes take place in the facility, requiring the use of significant quantities of hydraulic oils, acetone, ethylene glycol and other combustible liquids.

This paper will firstly describe the area under consideration in more detail and state what the fire protection objectives are. Several fire scenarios will then be discussed and example calculations presented to support a performance-based approach. The paper concludes with recommendations for the fire protection of the space.

DESCRIPTION

The area is a store room and a collection and staging area for drums and containers of flammable and combustible liquids and hazardous waste. The room is L-shaped, located on an external wall, and has a floor area of 66 m^2, as illustrated in Figure 1. The overall room dimensions are 12.1 m by 8.2 m and the floor to ceiling height is 5 m. A wooden tilt (garage) door in the exterior wall provides access to the outside for pick up and delivery of containers and drums. An interior door provides access to an adjacent processing area, and an additional door leads to an adjacent compressor room.

*Author is now with Connell Wagner Ltd., P.O. Box 1591, Wellington, New Zealand.

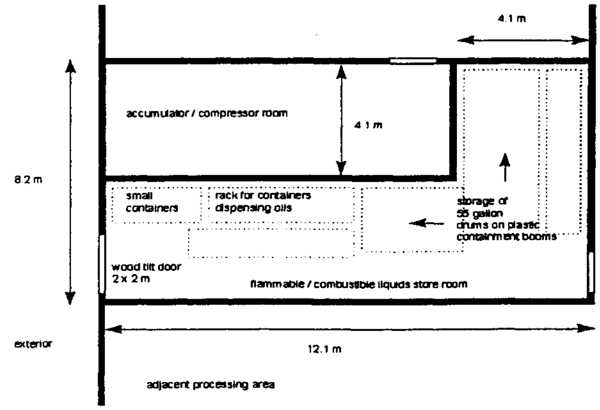

Figure 1. Layout of Flammable Liquid Storage Room.

Unprotected steel beams, run both longitudinally and transversely across the ceiling space, and provide support to a floor/ceiling system comprising 250 mm (10 in.) of concrete over exposed timber planks (sarking) which form the ceiling to the storage room. One of these beams is located only 2.1 m above the floor and may be exposed to fire on all sides. The walls of the room are lined with a mixture of painted plywood, plasterboard and fibreboard, and there are several openings where services pass through the walls into the adjacent processing area and into the compressor room. The walls are not fire rated, and openings are not fire protected.

The store room is primarily used for the transient storage of 55-gallon (208.2 L) steel drums of hydraulic and lubricating oils (e.g. Mobil DTE 24, 26) and hazardous waste and would typically hold a maximum of about thirty 55-gallon drums in a single tier. Drums are stored on end in a single tier and are usually placed on wood or plastic pallets (containment booms). Similarly sized drums of other fluids including acetone, ethylene glycol, trichloroethylene, epoxy resins and some rust-proofing liquids may also be present.

Hazardous waste materials may be stored in either steel or polyethylene drums (e.g. rinse water nickel solution was stored in polyethylene drums). The containment booms are designed to support four 55-gallon drums, and contain the leakage from 1.5 drums. A forklift is used to transport drums in and out of the room.

In addition to the drum storage, 9 steel containers (stored 3 by 3 within a steel frame rack) are stored on their sides and are used for dispensing various types of hydraulic and lubricating oils into smaller containers. Each of these containers measures 0.55 m by 0.55 m by 0.9 m deep (approximately 70 gallons each), and supplies oil to a series of tap valves at low level, being gravity fed by plastic hoses. Underneath the rack, a rectangular-shaped steel tray collects any oil residue. The height from the floor to the top of the top layer of these containers is 3.18 m.

The store room is protected with a ceiling sprinkler system utilizing 12.7 mm (1/2 in.) orifice (K factor = 5.6 gpm/psi$^{1/2}$) high temperature rated upright sprinklers at approximately 3 m (10 ft) spacings.

A sketch of the room layout is shown in Figure 1, and a general view of part of the room is shown in Figure 2.

Fire Protection Objectives

The primary objectives in specifying fire protection for the flammable and combustible liquid and hazardous waste store were identified as:

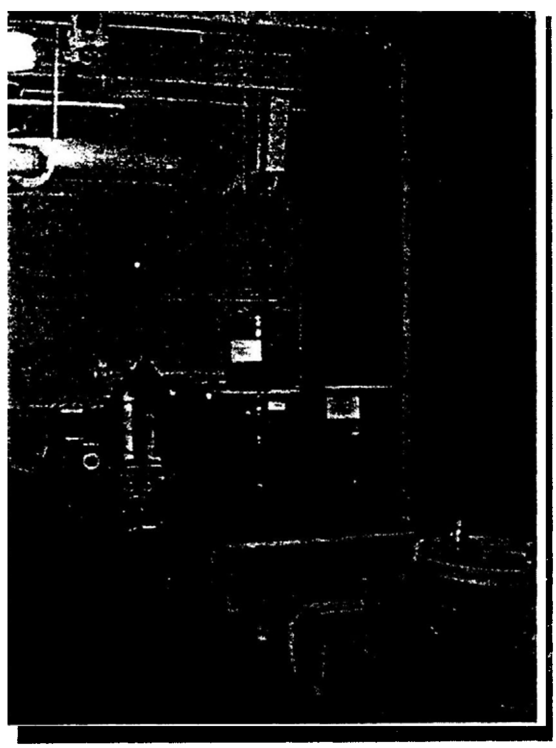

Figure 2. Part of Liquid Storage Room Showing Containment Booms and 55 Gallon Drums.

1. Prevent any rupturing of 55-gallon drums due to fire exposure. Limited breaching of small containers (<5 gallons) may be tolerated.

2. Prevent fire spread into the adjacent processing area by containing the fire to the store room.

3. Prevent major structural damage to the building.

Fuels Present and Potential Fire Scenarios

A range of petroleum-based hydraulic and lubricating oils may be present at any one time, as well as various other miscellaneous liquids such as acetone, ethylene glycol, trichloroethylene, etc. Typical properties for these types of liquids (from NFPA 325[1] and from specific product datasheets) are shown in Table 1.

Most of the liquids are classified as Class III combustible liquids, but acetone is classified as a Class IB flammable liquid according to the NFPA classification system[2].

Furthermore, the area itself would be classified as a Class I Division 2 location for electrical equipment, being a location in which flammable liquids are handled, but in which they would normally be confined within closed containers from which they can only escape in case of accidental rupture or breakdown. If the area were fully fire separated (to be recommended) this will not be a concern as there is no electrical equipment in the room.

The main ignition scenarios considered possible are:

1. The forklift knocks over or punctures a drum causing a liquid spill onto the floor of the room. If the liquid is acetone or another low flash point liquid, the vapors could be ignited by the exhaust manifold of the forklift or some other ignition source. The resulting pool fire then exposes other drums and containers in the room, which potentially may rupture and further add to the severity of the fire.

2. Ignition of the residue tray underneath the container rack (possibly due to heating from an exposure fire as described above), causes the flexible hoses connecting the metal tanks to their respective dispensing taps to soften, melt and release the tank contents. This could add up to a maximum of 630 gallons of fuel oil to the fire.

Requirements of NFPA 30

The store room is subject to the requirements of NFPA 30 Flammable and Combustible Liquids Code[2]. Most liquids to be stored have been established as having flashpoints greater than 93°C, being classified as combustible liquids IIIB. However, Class IB liquids may also be present (in particular acetone) and therefore these will generally govern protection considerations given by NFPA 30.

Table 1. Properties of Some Liquid Fuels Present

	Ethylene Glycol	Acetone	Mobil DTE26	Trichloroethylene
Flash-Point (°C)	111	-20	204	None
Ignition Temp (°C)	398	465		420
Boiling Point (°C)	197	56	316	87
Lower Flammability Limit % at 25°C	3.2	2.5		8
Upper Flammability Limit % at 25°C		12.8		10.5
Specific Gravity	1.115	0.8		1.5

Protection requirements using the proposed revisions to NFPA 30 have also been considered. The proposed Table 4-8.4 covers palletized storage of Class IB flammable liquid in 55-gallon metal drums (but only where relieving-style containers are used). It recommends foam-water protection using standard response ceiling sprinklers with standard or large orifices and a design density of 12.2 L/min/m^2 (0.3 gpm/ft^2) and a design area of 278.7 m^2 (3000 ft^2).

An alternative option, also using the proposed NFPA 30 recommendations, would be to store Class IB flammable liquids in metal containers with a maximum capacity of 5 gallons, and to protect the room with a water sprinkler system following Table 4-2.2. This would allow the use of standard-response ceiling sprinklers with standard or large orifices and a design density of 10.2 L/min m^2 (0.25 gpm/ft^2) and a design area of 139.4 m^2 (1500 ft^2) following the most restrictive of the 5-gallon containers of Class IB or the 55-gallon drums of Class IIIB.

NFPA 30 also requires a means to prevent spillage from flowing into adjacent building areas. This will require a sill to be constructed at the door between the storage room and the adjacent area.

Scenario Analysis

Confined Spill Limited By Room Floor Area

Using typical properties for a transformer oil, the maximum potential rate of heat release is estimated assuming the oil spill covers the entire 66 m^2 floor area of the store room. This rate of heat release will not be released in practice, but rather will be limited by the rate of air supply to the room.

The following properties are taken from Babrauskas[3] and Tewarson[4] for a transformer oil.

heat of combustion, $\Delta H_c = 46.4$ MJ/kg
mass loss rate per unit area, $\dot{m}''_\infty = 39$ g/m^{2}s
radiative loss fraction, $\chi_{rad} = 0.28$
convective loss fraction, $\chi_{con} = 0.56$

It will be assumed that the spill area is large enough for $\dot{m}'' = \dot{m}''_\infty$, and the heat release rate per unit floor area can be given by:

$$\begin{aligned}\dot{Q} &= \dot{m}''(\chi_{rad} + \chi_{con})\Delta H_c \\ &= (39\ \text{g/m}^2\text{s})(0.28 + 0.56)(46.4\ \text{kJ/g}) \\ &= 1520\ \text{kW/m}^2\end{aligned} \quad (1)$$

For an area of 66 m^2, this corresponds to a potential heat release of about 100 MW. To estimate what actual rate of heat release can be supported by the ventilation and air supply to the room, FPETool's Ventilation Limit subroutine[5] was used. Assuming two ventilation openings of 2 m high by 2 m wide and 2 m high by 1.6 m wide, the maximum rate of energy release achievable in the store room was estimated as 15.3 MW, as follows:

$$\begin{aligned}\dot{Q}_L &= 1500A_o\sqrt{h_o} \\ &= 1500(4\sqrt{2} + 3.2\sqrt{2}) \\ &= 15274\ \text{kW}\end{aligned} \quad (2)$$

Instantaneous Spill

Consider an instantaneous spill of a single 55-gallon drum of transformer oil, ignited at time = 0. The regression rate, y, is determined from the mass loss rate per unit area and the liquid density as follows:

$$y = \frac{\dot{m}''}{\rho} = \frac{0.039\ \text{kg/m}^2\text{s}}{760\ \text{kg/m}^3} = 0.05\ \text{mm/s} \quad (3)$$

Mudan[6] gives an expression for the maximum spill diameter for an instantaneous spill, D_{max} as follows, where V_L is the volume spilled (0.21 m^3).

$$\begin{aligned}D_{max} &= 2\left[\frac{V_L^3 g}{y^2}\right]^{1/8} \quad (4)\\ &= 2\left[\frac{((0.21\ \text{m}^3)^3)(9.81\ \text{m/s}^2)}{(5 \times 10^{-5}\ \text{m/s})^2}\right]^{1/8} = 6.9\ \text{m}\end{aligned}$$

The maximum rate of heat release from this diameter spill can then be determined using the same properties for the liquid as before, and the heat release rate per unit area previously calculated.

$$\dot{Q} = 1520\ \text{kW/m}^2 \times \frac{\pi(6.9\ \text{m})^2}{4} = 56.8\ \text{MW} \quad (5)$$

Thus it can be seen that a single drum of hydraulic oil contains more than enough fuel for burning to reach a ventilation-controlled state (15.3 MW) and that, for any fire in the store room involving more than a few gallons of fuel, there is likely to be a considerable amount of burning and flaming occurring at the vents, i.e. up the exterior of the building and into the interior processing area through unprotected service openings in the upper walls.

55-Gallon Drums Exposed to a Hydrocarbon Fire

The steel 55-gallon drums in the store room may potentially be exposed to a hydrocarbon fire, and it is desired to know approximately when the drums may be expected to rupture. The simplest hypothesis here would be to consider the liquid in the drums being uniformly heated until its boiling point is reached, at which time the rapid pressure increase may cause the drum to rupture. The first step is to establish whether uniform heating of the liquid is a valid assumption or whether boundary layer heating will predominate. For ethylene glycol, a non-dimensional number De is used as follows:

$$De = \frac{K^3(T_b - T_o)g\beta}{v\alpha(\dot{q}'')^3} \qquad (6)$$

For ethylene glycol, De = 99 for an exposure of $\dot{q}'' = 100$ kW/m^2. When the ratio $(\alpha/v)^{0.5}\, De^{0.25}$ is smaller than one, the wall heat flux is primarily absorbed within the thin liquid boundary layer and rapid temperature increases and vaporization can be expected according to Delichatsios[7]. In this example, the ratio is 0.28, thus the assumption of a uniformly heated liquid would not be valid, and substantial heating in the boundary layer would be expected. The predominant failure mode is usually at the bottom seam, resulting in possible drum rocketing. The non-uniform heating phenomenon is also expected to apply to the lubricating and hydraulic oils as well, given their properties. The United States Coast Guard carried out tests on some 55-gallon drum failure tests for lube oil, with drum breaching observed in about 2 minutes.

Fixed Tanks Exposed to a Hydrocarbon Fire

The scenario considered here is the heating and failure of the flexible hoses connecting the metal tanks holding various hydraulic and lubricating oils to their respective dispensing taps. Each of these tanks has a manually operated valve at the rear of the tanks to turn the flow on/off. It is understood their normal status would be in the flow on position, so that only the taps at the front need be operated by users filling small containers. The tanks are shown in Figure 3. Because only high flashpoint liquids (Class IIIB) are stored in these tanks at ambient temperatures, it will require a significant heat source for any released oils to be heated to their fire point temperatures and for ignition to occur. For this to happen, there is likely to be a large enough fire already in the room.

The heat release rate of oil flowing from the hoses and igniting will be estimated. The flow rate from each hose can be estimated assuming laminar flow, using the Hagen-Pouseuille equation, assuming the internal diameter of the hose is 12.7 mm (1/2 in.), the length of hose is 1.5 m, and the elevational height difference between the fluid in the tank and the end of the hose is 1 m. Using properties for Mobil DTE 26 oil (absolute viscosity is 0.056 Pa.s (at 40°C) and

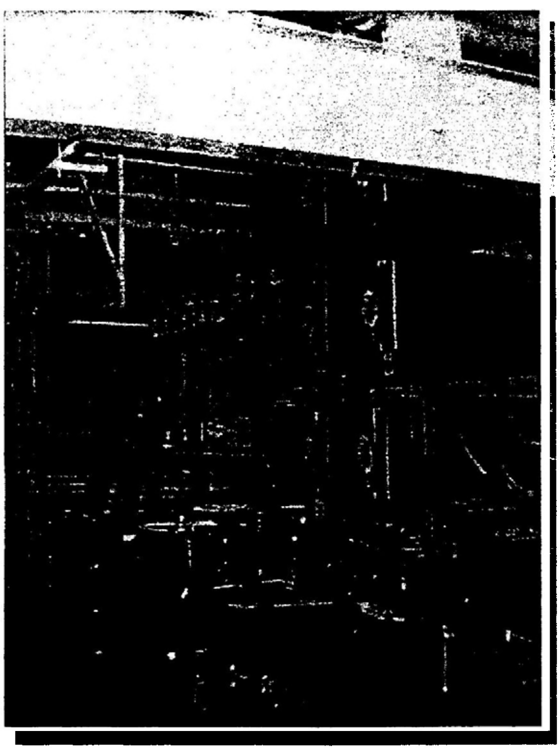

Figure 3. Rack Storage of Oil Filled Dispensing Containers in Liquid Storage Room.

density of the oil is 890 kg/m^3), the volumetric spill rate is given by:

$$\dot{V} = \frac{\pi d^4}{128\mu L}(pgH) = \frac{\pi(0.012\text{ m})^4(890\text{ kg/m}^3)(9.81\text{ m/s}^2)(1\text{ m})}{(128)(0.056\text{ Pa.s})(1.5\text{ m})} = 5.27 \times 10^{-5}\text{ m}^3\text{/s} \quad (7)$$

The mean velocity is given by:

$$u = \frac{4\dot{V}}{\pi d^2} = \frac{4(5.27 \times 10^{-5}\text{ m}^3\text{/s})}{\pi(0.012\text{ m})^2} = 0.47\text{ m/s} \quad (8)$$

Checking our assumption for laminar flow, based on Reynold's Number—

$$Re = \frac{up d}{\mu} = \frac{(0.47\text{ m/s})(890\text{ kg/m}^3)(0.012\text{ m})}{(0.056\text{ Pa.s})} = 88.9 \rightarrow \text{laminar flow} \quad (9)$$

Now, assuming that the pool burning rate will equal the spill rate, and assuming oil is spilling from all nine hoses, the heat release rate is given by:

$$\dot{Q} = \rho_L \dot{V} \Delta H_c \chi_{chem} = (890\text{ kg/m}^3)(9)(5.27 \times 10^{-5}\text{ m}^3\text{/s})(46.4\text{ MJ/kg})(0.84) = 16.5\text{ MW} \quad (10)$$

Thus, approximately 1.8 MW of heat release could result from the failure of each hose, giving a total of 16.5 MW should all hoses fail. The additional fuel load from the fixed tanks in terms of total energy content and additional heat release is significant. However, it will take a large-sized exposure fire to be in the room already for this scenario to eventuate. For this reason, the cost of installing a more sophisticated control system which will prevent the unwanted release of the container contents in a fire is considered to be unwarranted, and greater attention should be given to reducing the probability of an ignition occurring in the space.

A cheaper option would be to change operational procedures, so that the normal status of the tank valves and the tap valve at the front would be in the 'off' position. However, it is expected that this would cause some difficulty as the rear of the tanks are not very accessible, and a step ladder would be required to reach the top tanks. For this reason, such a practice would probably not be done, even if procedures were changed.

Sprinkler System Performance

According to recent hydraulic drawings for this part of the building, the occupancy has been classified as an ordinary hazard, with existing pipe sizing determined from pipe schedules. There are a total of 10 sprinklers in the store room, being upright 12.7 mm (1/2 in.) orifice (K=5.6 gpm/psi$^{1/2}$) with 141°C (286°F) temperature ratings. Clearly, according to NFPA 13[8], storage of significant quantities of flammable liquids represent an Extra Hazard Group 2 occupancy, and the design discharge able to be provided by the existing sprinklers is likely to be insufficient (probably in the range 0.1 to 0.2 gpm/ft^2).

The ceiling also has substantial obstructions, in particular the steel beams which span the room in perpendicular directions and which are expected to partially obstruct the water spray. Because of the unusual arrangement of steel beams which run through the space, and their significant obstructive effect, NFPA 13 would require the sprinkler deflector be positioned 1.83 m (6 ft) from the side of the obstruction. This distance is not currently provided.

In assessing the effectiveness of the ceiling sprinkler system, a large spill may not necessarily be the most challenging fire scenario. We will therefore consider a pool fire confined to one of the containment booms giving an equivalent diameter of 1.35 m, and an area of 1.44 m^2. Using the same heat release rate of 1520 kW/m^2 (calculated earlier) gives a design fire with a steady state heat release rate of 2.2 MW.

The computer program DETACT from FPETOOL[5] was used to estimate the actuation time of a 141°C (286°F) temperature rated sprinkler, with a response time index (RTI) of 166 ms$^{1/2}$ at a radial distance of 2.16 m (10 ft by 10 ft spacing) from the fire axis. The ambient temperature was assumed to be 20°C and the height of the ceiling above the fuel 4.8 m. Under these conditions, DETACT predicts that the sprinkler will never actuate. Therefore, any drum exposed to this fire may continue to be heated until the pressure inside the drum is sufficient to cause it to rupture, or until the fuel is exhausted. In addition, the plastic containment boom (pallet) will eventually melt, causing the fire to spread laterally.

The minimum fire size needed to actuate the sprinkler under these conditions was estimated by DETACT to be 2420 kW. This assumes that the ceiling is unconfined, there is no hot layer development, and that the sprinkler head is located at the distance below the ceiling corresponding to the maximum ceiling jet velocity, all of which were not true, so the calculation must be regarded as being a first-order estimate. Repeating the calculation for an ordinary temperature-rated sprinkler of 74°C (165°F) reduces the predicted actuation time to around 60 s and a minimum fire size required for actuation of about 720 kW. It is recommended that the sprinklers should be changed to the lower rating. This will cause the first few sprinklers to operate sooner and reduce the probability of a drum BLEVE.*

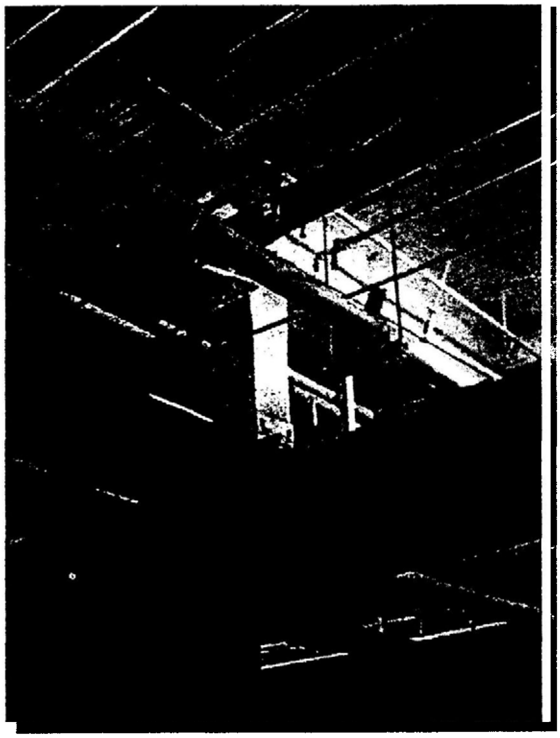

Figure 4. Ceiling Structure in Flammable Liquid Storage Room.

Fire Resistance of Structural Steel

Two unprotected steel I-beams run across the ceiling of the store room. One beam runs longitudinally directly beneath the ceiling at a height of 4.5 m above the floor, while the other runs transversely at a lower height of 2.1 m above the floor. This latter steel beam provides support to a timber column support, which in turn provides support to the first steel beam. Both beams support an upper concrete floor. The arrangement of these beams is shown in Figure 4.

It is desired to know for how long the unprotected steel beams will be able to resist a fully developed fire in the store room. The lower beam will be considered since it can be fully engulfed by fire on all four sides (the beam directly beneath the ceiling is exposed on only three sides) and it provides support to the second beam. At only a height of 2.1 m above the floor, the beam is expected to be fully engulfed by flames from a pool fire and therefore will be subjected to both radiative and convective heating. The properties and parameters used in the analysis for the steel beam are shown in Table 2.

*Boiling Liquid Expanding Vapor Explosion.

The steel mass per unit length, W, for the beam is given by:

$$\frac{M_s}{L} = \frac{\rho V}{L} = \rho A_c = (7850\ \text{kg/m}^3)(0.0092\ \text{m}^2) = 72.2\ \text{kg/m} \tag{11}$$

An empirical expression (converted to metric by the authors) is given by Lie[9] for the fire resistance (R in minutes) of an unprotected steel section as follows:

$$R = 74.9\left(\frac{W}{D}\right)^{0.7} = 74.9\left(\frac{72.2\ \text{kg/m}}{1520\ \text{mm}}\right)^{0.7} = 8.9\ \text{min} \tag{12}$$

Table 2. Selected Properties of Steel

Density of the steel (ρ):	7850 kg/m^3
Cross-sectional area of steel section (A_c):	0.0092 m^2
Heated perimeter of the steel section (D):	1520 mm

The time to failure of the beams is therefore relatively short and additional fire resistance protection is recommended. (NFPA 30 asks for a 2-hour fire resistance for interior walls and ceilings.)

Lie[9] also gives an expression for steel protected by gypsum plasterboard.

$$R = 57.37 \left(\frac{hW'}{D}\right)^{0.75} \qquad (13)$$
$$W' = 0.672W + \left(\frac{hD}{1856}\right)$$

Substituting a gypsum board thickness (h) of 48 mm (3 × 16 mm) gives a fire resistance time of 123 minutes. This thickness of protection (48 mm) relates to a 123 minute exposure to a standard time-temperature furnace fire, which may or may not bear any resemblance to the actual exposure severity in this situation. This calculation is a first order estimate and more sophisticated techniques could be used as desired. Therefore, we will also use a method developed by Barnett[10] which takes into account a normalized heat load for a natural fire. To use this method, we first need to estimate the fuel loading per unit floor area in terms of wood mass equivalent.

Assume that there are 30 drums of hydraulic oil present, giving a total of 1650 gallons. The volume of oil is:

$$\text{volume} = 1650 \text{ gal} \times \frac{0.208 \text{ m}^3}{55 \text{ gal}} = 6.24 \text{ m}^3 \qquad (14)$$

$$\text{mass of oil} = 6.24 \text{ m}^3 \times 902 \text{ kg/m}^3 = 5628.5 \text{ kg} \qquad (15)$$

But we have already estimated that only 15.3 MW out of a maximum possible 100 MW will actually be released inside the compartment, and therefore heat up the structure, so that the mass of oil burning in the compartment becomes 5628.5 × 0.153 = 861 kg. The equivalent mass of wood is:

$$\text{mass of wood} = 861 \text{ kg} \times \frac{46.4 \text{ MJ/kg-oil}}{16 \text{ MJ/kg-wood}} = 2497 \text{ kg-wood} \qquad (16)$$

The wood equivalent load per unit floor area is therefore:

$$\text{fuel load} = \frac{2497 \text{ kg-wood}}{66 \text{ m2}} = 38 \text{ kg-wood/m}^2 \qquad (17)$$

Applying Barnett's method indicates that at least 28 mm of gypsum plasterboard protection (assumed properties k = 0.19 W/mk; ρ = 910 kg/m³; c = 1200 J/kgK) would be necessary in order to prevent the steel beams from reaching an assumed critical temperature of 530°C. The calculation was done using a spreadsheet and shows that the fire scenario considered here would be equivalent to an exposure of about 130 minutes in a standard fire resistance furnace test. A copy of the spreadsheet results are shown in Figure 5.

Barrier Performance

The existing walls would be totally ineffective in containing the fire to the room. Not only are combustible materials used (such as painted plywood, exposed timber, fiberboard and timber boards), but there are also significant openings present into the adjacent processing area and into the compressor room. These walls will not act as effective fire separations. Although a reasonably close-fitting steel pair fire door is used for access to the room from the processing area, no self-closing device is fitted to ensure it is likely to be closed in the event of fire and thus ensure its behavior as an effective fire barrier. It is recommended that the fire resistance of these fire separations be upgraded to 2 hr approved fire resistant assemblies with two layers of 16 mm gypsum plasterboard, based on the analysis using Barnett's method in the previous section.

INSULATED STEEL STRUCTURES EXPOSED TO FIRE

REFERENCE Barnett, J.R. 1991. A New Design Approach For Steel Structures Exposed to Fire J. of Fire Protection Engineering, 3(1), pp1-8

Compartment Data		**Openings Data**	
Length (m)	12.1	Vent Width (m)	2
Width (m)	5.45	Vent Height (m)	2
Height (m)	4.9		
Fuel Data		**Boundary Data**	
Cellulosic Fire Load Per Floor Area (Kg/m2)	38	Type I (brick & plaster)	2
		Type II (gypsum)	
Steel Data		**Thermal Properties of Insulation**	
Critical Steel Temp (K)	803	Conductivity (W/mK)	0.19
		Specific Heat (J/Kg K)	1200
		Density (Kg/m3)	910

Inner Surface Area of Boundary less Floor Area		237.935	m2
Opening Area		4	m2
Area Compensated Ventilation Parameter		0.023774788	m0 5
Cellulosic Fuel Mass		2505.91	kg
Rate of Mass Loss of the Fuel		0.50	kg/s
Fire Duration		4969.32	s
Coefficients	a	1159.15	
	b	0.05	
	c	-639.05	
	d	-0.02	
Average Fire Gas Temperature		1278.28	K
Normalised Heat Load for Natural Fire		78372.41	K s0 5
Required Thickness of Insulation		0.028	m
Equivalent Fire Resistance Time		130	minutes

Figure 5. Calculation of Required Thickness of Insulation for Steel Beam Protection.

Fire Protection Recommendations

This analysis has shown that a potential exists for a serious fire in the flammable liquid and hazardous waste store with the likelihood of fire spread into the adjacent processing area. It is also apparent that the ceiling sprinkler system will probably not be able to control a fire in this space, particularly a fire under the oil dispensing rack containers, which would be shielded from ceiling sprinkler spray, and in which the release of the container contents would result in an elevated, three-dimensional flowing fire. The best strategies are therefore likely to be:

1. Ensure the fire is contained to the cut-off room, and prevented from spreading to the adjacent processing area and nearby compressor room without causing major structural damage.

2. Reduce ignition sources by minimizing storage and dispensing of Class I and Class II flammable liquids (e.g. acetone) in the area.

Our specific recommendations for the flammable liquid and hazardous waste store are:

1. Upgrade the fire resistance of walls and seal all openings around service penetrations with approved fire stopping systems (rated to 2 hours), to help ensure the fire is contained in the room and does not spread to the processing area.

2. Add fire protection to the steel beams, and to the timber column to prevent the steel from reaching a structurally critical temperature, with 2 layers of 16 mm fire-resistant gypsum plasterboard or equivalent material to give a notional 2 hour fire rated protection.

3. Add an approved self-closing device to the steel door between the store and the processing area, to help ensure the door is closed during a fire incident, and fire is contained to the cut-off room.

4. Limit the storage of flammable (Class 1B) liquids (e.g. acetone) to 5-gallon containers instead of 55-gallon drums, and provide water-based protection using the existing sprinkler system.

5. Change the sprinklers to ordinary 74°C (165°F) rated heads to reduce the likelihood of drums rupturing, by providing cooling water for drums at an earlier time.

6. Avoid the dispensing of any Class I flammable liquids (e.g. acetone) in the store room.

Acknowledgements

The authors wish to thank Professor Robert Zalosh of Worcester Polytechnic Institute for the insight he provided into the many different facets of industrial fire protection.

Nomenclature

d	pipe diameter (m)
g	gravity (=9.81 m/s^2)
h	thickness of insulation (mm)
h_o	height of ventilation opening (m)
m	mass of fuel (kg)
u	velocity (m/s)
y	fuel regression rate (mm/s)
A_o	area of ventilation opening (m^2)
A_c	cross-section area (m^2)
D	diameter of pool fire (m) or heated perimeter of steel (mm)
De	non-dimensional number
H	height (m)
K	constant
M	mass (kg)
L	length (m)
R	fire resistance time (min)
T	temperature (°C)
T_o	ambient temperature (°C)
V	volume (m^3)
W	steel mass per unit length (kg/m)
W'	steel and insulation mass per unit length (kg/m)
$\dot{V}$	volumetric flow rate (m^3/s)
$\dot{q}$	rate of energy release (kW)
$\dot{Q}_L$	ventilation-limited rate of energy release (kW)
$\dot{q}''$	heat flux (kW/m^2)
χ	energy loss fraction
ΔH_c	heat of combustion (kJ/kg)
ρ	density (kg/m^3)

α	thermal diffusivity (m^2/s)
β	constant
μ	absolute viscosity (Pa.s)
υ	kinematic viscosity (m^2/s)

Subscripts

rad	radiation
con	convection
chem	chemical
max	maximum
L	liquid
b	boiling
s	steel

Superscripts

$\cdot$	per unit time
$''$	per unit area
$'''$	per unit volume

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