Risk-Based Approach - Fires

Introduction to Fires and Dynamic Thermal Stress Analysis

An ioMosaic White Paper

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Abstract

This manuscript explains the fire phenomena and introduces the different types of industrial fires that should be identified and characterized during the development of a risk-based quantitative assessment; i.e., flash fires, pool fires, jet fires and fireballs. It addresses specific criteria for the following primary fire types with potential for domino effect; i.e., pool and jet fires. An advanced and time efficient quantitative approach is proposed for accurately estimating the Time to Failure (TTF) of process equipment or any other type of structure of interest being impacted by fires. The approach is suitable for ensuring which are the most appropriate risk reduction measures (active and passive) to be considered during the decision-making process and to predict if there is enough time to either prevent or mitigate the fire outcomes with the aim to prevent escalation; i.e., Dynamic Thermal Stress Analysis (DTSA).

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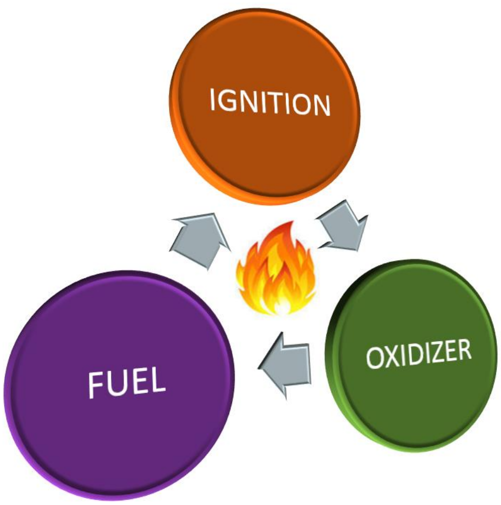
Introduction to Fires

Definition

Fire is the rapid exothermic oxidation of an ignited fuel. The fuel can be in solid, liquid or vapor form. Vapor and liquid fuels are generally easier to ignite. The combustion always occurs in the vapor phase; liquids are volatized and solids are decomposed into vapor before combustion. When fuel, oxidizer and an ignition source are present at the necessary levels, burning will occur **[1]**. The essential elements for combustion are fuel, an oxidizer and an ignition source; i.e., the fire triangle (see **Figure 01**).



This means a fire will not occur if:

1. Fuel is not present or is not present in sufficient quantities.
2. An oxidizer is not present or is not present in sufficient quantities.
3. The ignition source is not energetic enough to initiate the fire.

Figure 01: The Fire Triangle

Some of the commonly used definitions associated with fires and explosions are given by reference **[1]**:

- **Combustion or fire**: combustion or fire is a chemical reaction in which a substance combines with an oxidant and releases energy. Part of the energy released is used to sustain the reaction.
- **Ignition**: ignition of a flammable mixture may be caused by a flammable mixture encountering a source of ignition with sufficient energy or the gas reaching a temperature high enough to cause the gas to autoignite.
- **Autoignition temperature**: a fixed temperature above which adequate energy is available in the environment to provide an ignition source.

- **Flash point**: lowest temperature at which it gives off enough vapor to form an ignitable mixture with air. At the flash point the vapor will burn but only briefly; inadequate vapor is produced to maintain combustion. The flash point generally increases with increasing pressure. There are several different experimental methods used to determine flash points. Each method produces a somewhat different value. The two most commonly used methods are open cup and closed cup, depending on the physical configuration of the experimental equipment.

- **Fire point**: lowest temperature at which a vapor above a liquid will continue to burn once ignited. The fire point temperature is higher than the flash point.

- **Flammability limits**: vapor-air mixtures will ignite and burn only over a well-specified range of compositions. The mixture will not burn when the composition is lower than the Lower Flammable Limit (LFL); the mixture is too lean for combustion. The mixture is also not combustible when the composition is too rich; that is, when it is above the Upper Flammable Limit (UFL). A mixture is flammable only when the composition is between the LFL and the UFL. Commonly used units are volume percent fuel (percentage of fuel plus air).

  Note: Lower Explosion Limit (LEL) and Upper Explosion Limit (UEL) are used interchangeably with LFL and UFL.

Industrial Fires

Industrial fires can have very different characteristics and encompass an extensive range of size. Fire properties are influenced by leakage rates and their time dependence, type of flammable substance burning, storage and discharge conditions, surrounding topside structures and equipment and ambient wind conditions. Despite the large number of possible fire events, few categories of industrial fires are relevant for risk assessment and for escalation leading to domino effect **[2]**.

The following contents describe the most relevant industrial fire types to be identified in a process facility; i.e., pool fires, jet fires, flash fires and fireballs.

Pool Fires

Pool fires consists in the uncontrolled combustion of vapors generated from a pool of a flammable liquid. The fire creates a steady radiation source resulting from a duration that may be more relevant and higher than jet fires. Even if the heat load associated with pool fires is usually lower than that associated with jet fires, due to the limited convective term associated to the flame velocity, an engulfment in flames may cause failure of the target building. In case of a target building receiving a steady heat radiation but not engulfed in flames, the analysis should be addressed considering the intensity of heat radiation **[2]**. Pool fires tend to be localized in effect and are mainly of concern in establishing the potential for domino effects and employee safety zones, rather than for community risk. The primary effects of such fires are due to thermal radiation from the flame source. Issues between tanks and interplant spacing, thermal insulation, fire wall specification, etc., can be addressed based on specific consequence analyses for a range of possible pool fire scenarios **[3]**.

Drainage is an important consideration in the prevention of pool fires; i.e., if the material is drained to a safe location, a pool fire is not possible. The important considerations are that (1) the liquid must be drained to a safe area, (2) the liquid must be covered to minimize vaporization, (3) the drainage area must be far enough away from thermal radiation fire sources, (4) adequate fire protection must be provided, (5) consideration must be provided for containment and drainage of fire water and (6) leak detection must be provided **[3]**.

Jet Fires

Jet Fires are characterized by a momentum dominated release and high levels of thermal radiation resulting from well mixed combustion. Jet fires are considered among the more critical fire events because of potential escalation due to high heat loads and flame temperatures. Besides the contribution of radiation, the convective term is also considerable due to high flame speed **[2]**. The heat load is higher than in low-velocity flames; e.g., pool fires.

Flash Fires

Flash fire when a flame front propagates (relatively slowly) through a flammable vapor cloud without producing significant overpressure. The flash fire phenomenon is characterized by a low flame speed; hence typical duration may range from few milliseconds to few seconds for large stratified flammable clouds **[2]**. Flash fires have a characteristic short duration that is a few orders of magnitude lower than the Time to Failure (TTF) due to heat radiation of typical process plant permanent or portable buildings or process equipment. Consequently, flash fires outside buildings/structures are not normally considered in facility siting studies.

The literature provides little information on the effects of thermal radiation from flash fires, probably because thermal radiation hazards from burning vapor clouds are considered less significant than possible blast effects. Flash combustion of a vapor cloud normally lasts no more than a few tenths of a second. Therefore, the total intercepted radiation by an object near a flash fire is substantially lower than in the case of a pool fire **[3]**.

Typically, the burning zone is estimated by first performing a dispersion model and defining the burning zone from the ½ LFL limit back to the release point, even though the vapor concentration might be above the UFL. Turbulence induced combustion mixes with air and burns it. To compute the thermal radiation effects produced by a burning vapor cloud, it is necessary to know the flame's temperature, size and dynamics during its propagation through the cloud. Thermal radiation intercepted by an object in the vicinity is determined by the emissive power of the flame, the flame's emissivity, the view factor and an atmospheric-attenuation factor **[3].**

Fireballs

Fireballs resulting from the rapid involvement of a large amount of flammable material are also characterized by high levels of thermal radiation. A fireball has a limited duration, although it is longer than the one of a flash fire. Two situations should be considered for domino effect and escalation assessment: (1) flame engulfment if the target building or process equipment is comprised within the cloud extension and (2) radiation from a distance source without flame impingement for target locations at distances higher than the flame radius. The resistance of typical process plant permanent and portable buildings allows for a TTF higher than the expected duration of the fireball. For this reason, fireballs are not normally considered in facility siting evaluations.

All fire types addressed above are subject to analysis during the development of a risk-based quantitative assessment. Both effects and human vulnerability models are applied for characterizing the risk level of the facility under analysis by applying all contents and principles illustrated in references **[4]**, **[5]**, **[6]**, **[7]**, **[8]**, **[9]**, **[10]**, **[11]**, **[12]**. After characterizing the individual frequency of each fire identified based on likelihood estimation, associated effects using consequence modeling and by applying human vulnerability models (e.g., thresholds, probit equation), the generation and analysis of the following specific results is critical to comply with the main objectives of the study:

- Individual Risk Contours for individual risk characterization
- FN curves for societal risk characterization
- Heat Flux Exceedance Curves (HFEC) with the aim to fully characterize target locations; i.e., identification of exceedance heat flow values impacting the location due to fires
- Thermal Radiation Risk Contours with the aim to provide with fire zones of interest for emergency planning purposes

When addressing process equipment, it is required to conduct further analysis for those fires capable of triggering escalation, which can lead to secondary hazardous scenarios with potential to increase the actual risk level predicted. These fires are mainly pool fires and jet fires, which are intensive and localized and could cause domino effect due to thermal radiation and/or direct fire impingement to other process equipment located in the surrounding area of the primary fires **[13]**, **[14]**.

The following section is intended to provide with a detailed characterization of fires capable of escalation and domino effect. Correlating the relevant features of the industrial fires with the potential secondary effects due to the ignition of flammable material involved in domino accidents.

Table 01 classifies and correlates the different fires identified in the process industry with escalation criteria based on the heat load received by the target **[2]**. Based on contents listed in **Table 01** and if all potential fires impacting a target location (equipment) have been already identified and characterized during the risk-based quantitative assessment, the analysis of the domino effect can be performed by categorizing the type of process equipment (atmospheric or pressurized) and the type of fire. This categorization allows the user to perform a dedicated domino effect analysis by using dedicated heat flow thresholds (i.e., Q_{HL} in [$kW \cdot m^{-2}$]) as a function of process equipment type.

Table 01: Fires Evidencing Escalation Based on Heat Load Received by the Target [2]

Q_{HL} in [kW·m^{-2}]: Thermal Flow received by the fire

Features Relevant for Escalation	Confined Jet fire	Open Jet Fire	Confined Pool/Tank Fire	Open Pool Fire	Fireball	Flash Fire
Combustion Mode	Diffusive	Diffusive	Diffusive	Diffusive	Diffusive	Premixed
Total Heat Load [kW·m^{-2}]	150-400	100-400	100-250	50-150	150-280	170-200
Radiative Contribution [%]	66.7-75	50-62.5	92-100	100	100	100
Convective Contribution [%]	25-33.3	37.5-50	0-8	0	0	0
Flame Temperature Range [K]	1,200-1,600	1,200-1,500	1,200-1,450	1,000-1,400	1,400-1,500	1,500-1,900
Atmospheric Equipment - Escalation Criteria for Fire Impingement	Possible	Possible	Possible	Possible	Q_{HL} > 100	**Note 01**
Pressurized Equipment -Escalation Criteria for Fire Impingement	Possible	Possible	Possible	Possible	Unlikely	Unlikely
Atmospheric Equipment - Escalation Criteria for Distance Source Radiation	Q_{HL} > 15	Q_{HL} > 15	Q_{HL} > 15	Q_{HL} > 15	Q_{HL} > 100	Unlikely
Pressurized Equipment - Escalation Criteria for Distance Source Radiation	Q_{HL} > 40	Q_{HL} > 40	Q_{HL} > 40	Q_{HL} > 40	Unlikely	Unlikely

Note 01: Flammable vapors ignition for floating roof tanks

Behavior of Equipment Exposed to Fire – Domino Effect

The analysis of fire scenarios relevant for escalation demonstrated in several situations that the resistance of the target equipment needs to be specifically evaluated, accounting for the characteristics of the fire scenario and the actual mode of exposure to fire. A quantitative assessment of escalation is proposed for the prediction of the Time to Failure (TTF) of equipment exposed to fires. The behavior of equipment exposed to fire shows that the key issue in the evaluation of the credibility of escalation by fire is the determination of the TTF of the target equipment. This represents the available time lapse for the activation of emergency procedures and of mitigation devices, as well as for the deployment of emergency teams aimed at the mitigation and/or suppression of the primary fire. It may be reasonably assumed, based on experience, that the full and correct activation of the planned specific emergency measures should prevent, in general, escalation triggered by fire **[2]**. Therefore, besides the prevention of primary fires, all the available strategies aimed at the prevention of escalation caused by fires prescribe measures to delay or eliminate secondary equipment failure, to guarantee a sufficient Time to Effective Mitigation (TEM). That is assumed as the time needed to put in place emergency measures that will effectively prevent the escalation caused by fire. Note that the quantitative approach proposed for estimating the TTF of an equipment or structure being impacted by primary fires is intended to provide with the actual TEM to ensure mitigation plan effectiveness and to be useful when conducting advanced sensitivity analysis by considering different potential risk reduction measures, such as passive or active protection systems intended to minimize the likelihood of escalation:

- Passive Protection Systems: systems or barriers which do not require either power or external activation to trigger the protection action, usually based on the implementation of a set of barriers with the aim to delay the equipment failure. As a result, passive protection systems provide additional time for the implementation of active protections (e.g., firefighting) or of mitigation measures (e.g., blowdown and depressurization systems). Some examples of passive protection systems are the following: pressure relief devices intended to limit the equipment internal pressure and fireproofing insulation **[2]**.

- Active Protection Systems: systems or barriers which require an external automatic activation and are normally composed of three subsystems in a chain: a fire or gas detection system, a logic system able to advice the operator or sequence of automatic actions to be performed and an actuation system (human, mechanical or instrumented). The active protection systems are intended to: (1) deliver firefighting agents such as spray systems, sprinklers, water deluge systems and/or (2) Emergency Shut-Down and Emergency Depressurization systems **[2]**.

Dynamic Thermal Stress Analysis and Wall Segmentation Approach

Based on the contents discussed above and since fire is the primary event, an accurate model to predict the heat load due to fire is critical. The last revision of API Standard 521 **[15]** includes a fundamental equation for estimating the heating rate into the equipment walls:

$$q_w = \alpha_w \varepsilon_f \sigma T_f^4 + h\left(T_{f,g} - T_{w,t}\right) - \varepsilon_w \sigma T_{w,t}^4 \qquad \textbf{Equation 01}$$

The first term is the flame radiative heat flux into the external wall or insulation surface. The second term is the hot combustion gases convective heat flux into the external wall or insulation surface. The third term is the heat flux that is re-radiated by the external wall or insulation surface **[16]**.

When SI units are used, $\boldsymbol{q_w}$ is the net heat flux reaching the wall or insulation surface in $W \cdot m^{-2} \cdot K^{-1}$, $\boldsymbol{\alpha_w}$ is the external wall surface or insulation absorptivity, $\boldsymbol{\varepsilon_f}$ is the flame surface emissivity, $\boldsymbol{\sigma}$ is the Stefan–Boltzmann constant (i.e., 5.67E-08 $W \cdot m^{-2} \cdot K^{-4}$), $\mathbf{T_f}$ is the flame surface temperature in K, $\boldsymbol{h}$ is the combustion gases convective heat transfer coefficient in $W \cdot m^{-2} \cdot K^{-1}$, $\boldsymbol{T_{f,g}}$ is the combustion gases temperature in K, $\boldsymbol{T_{w,t}}$ is the time dependent wall surface temperature in K and $\boldsymbol{\varepsilon_w}$ is the external wall or insulation surface emissivity. Recommended values are provided by API Standard 521 **[15]** and reference **[16]**. **Equation 01** illustrates that the heat load is a combination of the heat transferred from the fire to the vessel walls by radiation and convection. As the vessel receives the heat load, its shell heats up and heat is transferred into the liquid and vapor contents. The wall temperature increases and consequently the internal fluid temperature rises. As a result, the Ultimate Tensile Strength (UTS) of the material of construction decreases.

Additionally, the internal pressure rises (i.e., hoop stress) due to the heating of vessel contents. The wall temperature in the region of the gas phase rises rapidly due to the poor heat transfer between the gas phase and vessel wall.

The wall temperature at the wetted region in contact with the liquid has a temperature close to the liquid temperature due to the high rate of heat transfer between the stored liquid and vessel wall. Typical failures are expected to occur at the vapor/liquid interface due to the difference in temperature between the vapor space hot metal and liquid space cooler metal **[17]**.

The fire heat load is one of the key parameters that impact the duration between the fire starting-point and the eventual equipment failure leading to a Loss of Containment scenario (LOCs). This time lapse can be as small as few minutes (e.g., flame jet impingement causes high intensity localized heating) or longer in duration (e.g., pool fire engulfment, partial engulfment, thermal radiation from a pool fire near the vessel under analysis). This time lapse, called Time to Failure (TTF), is an important parameter that is calculated for the protection and prevention of escalation triggered by fire exposure (i.e., the domino effect) **[2]**, **[14]**.

The accurate prediction of the conditions at the TTF forms the basis for consequence analysis (i.e., how the available internal energy in the system is being transformed). A source of fragmentation and deformation energy for the vessel shell, kinetic energy imparted to contents and fragments and blast wave energy. Therefore, the TTF and associated conditions are valuable parameters to be characterized because both provide information on the likeliness of a catastrophic failure due to fire exposure and show how severe the associated impacts are; i.e., domino effect and escalation analysis. Estimating the TTF is based on having detailed models for predicting the fluid dynamics of vessels containing liquids, vapors and multi-phase fluids with and without chemical reactions. These models often use an equation of state based approach to represent the conditions and the vapor-liquid equilibrium behavior of the vessel contents in addition to the internal energy and constant volume constraints. Vessel wall dynamic models also include incoming and outgoing fluid streams to connect a vessel to other vessels and to connect relief and process lines to the top and the bottom of the vessel. The flow dynamics through the top and bottom connections and/or relief lines should include vapor flow, liquid flow, sub-cooled liquid flow and multiphase flow with/without slip **[18]**.

The vessel dynamics model in SuperChems™ **[19]**, a component of ioMosaic's Process Safety Office™ include wall-fluid heat transfer dynamics. To account for detailed vessel wall and fluid heat transfer dynamics, the simulated equipment is segmented into multiple zones, as shown in **Figure 02**.

Detailed heat transfer to/from the surroundings and between the zones is dynamically accounted for. The ability to divide equipment into multiple segments allows close examination of the fluid dynamics and vessel wall thermal effects. Other valuable applications of the segmentation approach include the modeling of external fire, localized heating and flame jet impingement. Once segmentation is defined, heat transfer analysis is applied per wall segment. Ambient to wall segment heat transfer options include insulation, solar heating, rain, water sprays, pool fires and flame jets (i.e., radiation and convection). The heat transfer from wall segment to fluid includes radiation, natural convection, forced convection, film boiling and pool boiling. It is important to mention that T_f and $T_{f,g}$ temperatures shown in **Equation 01** above are modeled as constant values during the simulation.

The vessel dynamics codes can rely on published heat transfer correlations to model the heat transfer between the wall segments and the vessel contents although it is possible to define fixed values for the heat transfer coefficients. The cited dynamics codes allow to specify vessel internals which allow heat transfer and surface adsorption reactions.

When considering the installation of emergency relief systems in process equipment, it is important to address the complex hydrodynamic phenomena due to vapor and liquid in motion. The question of vapor versus two-phase vapor-liquid relief depends primarily on the prevailing disengagement regime, that is, bubbly and/or foamy-like behavior, or churn-turbulent behavior. The former regime is indicative of relatively little vapor disengagement. In contrast, significant vapor disengagement is possible with the churn-turbulent regime. In other words, the vapor-liquid phase ratio entering the relief device can differ substantially from the average quality in the vessel **[20]**.

Vessel flow models estimate the liquid swell and degree of vapor-liquid disengagement as a function of vapor output. The vapor may be generated uniformly throughout the liquid volume, formed preferentially near the top of the liquid due to hydrostatic head and recirculation effects, sparged at the bottom, or generated at the walls due to external heating. These vessel flow models are coupled with vent flow capacity models at a given vessel pressure to determine the vapor mass fraction and the total mass flow rate entering the vent line which in turn is used to determine the vent volumetric discharge rate.

The vessel flow models implemented in SuperChems™ **[19]** are formulated from drift flux theory and correlated with available test data. The key vessel flow model parameters are the average void fraction, the vapor superficial velocity at the liquid surface and the characteristic bubble rise velocity. The vessel flow models define the relationship between these three parameters **[18]**.

Figure 02: SuperChems™ [19] Segmentation Scheme

Figure is missing

Using the wall segmentation approach, the metal wall segment temperatures and the pressure histories are evaluated as a function of time. It is possible to then estimate the internal hoop stress and the UTS of the metal segments as a function of time and temperature. Simulations typically consider 2/3 of the UTS to be the failure boundary. A safety factor is normally recommended to account for uncertainties associated with metal properties, defects and calculation methods **[16]**.

Consequences Due to Catastrophic Equipment Failure Due to Fire Exposure

The TTF prediction provides the lapsed time from the fire start (i.e., valuable information for the decision-making process) and defines the associated temperature, pressure, fluid composition and mass remaining in the equipment at the failure point. These conditions characterize the internal available energy in the system. A Boiling Liquid Expanding Vapor Explosion (BLEVE) is a potential outcome. Upon vessel failure, the sudden expansion and/or flashing of the vessel contents creates overpressure.

Rapid depressurization of a vessel can lead to intensive and/or explosive boiling of the liquid contents. Depressurization can be attributed to flow and/or expansion. The pressure will drop below the saturation point following rapid depressurization and the rate of pressure drop impacts this pressure undershoot which in turn has an effect to the superheat available for bubble nucleation. Large depressurization rates can lead to large undershoots and large bubble nucleation superheats. The pressure will recover when the pressure rise caused by bubble generation is equal to the rate of imposed pressure drop at flashing inception. A sharp pressure rise caused by spontaneous bubble generation follows. As the initial temperature/pressure reaches the superheat limit, depressurization rates required to cause a metastable liquid to form become smaller.

If the vessel contents undergo isentropic expansion, the total amount of internal available energy stored in the superheated liquid and/or vapor can be calculated **[18]**. The amount of internal available energy is the difference between the initial internal energy of the vessel contents before failure and the final internal energy of the resulting vapor-liquid mixture (under equilibrium) minus the PV work done on the atmosphere due to volumetric expansion (blast wave energy).

Conclusions

This paper introduces the different types of industrial fires that should be identified and characterized during the development of a risk-based quantitative assessment. It explains specific criteria focused on those primary fire types with potential for domino effect; i.e., pool and jet fires. An advanced and time-efficient quantitative approach has been proposed for accurately estimating the Time to Failure (TTF) of process equipment being impacted by fires. The approach is useful for ensuring which are the most appropriate risk reduction measures (active and passive) to be considered during the decision-making process.

Once the basis of the risk-based quantitative assessment is already developed, equipment that requires a more detailed analysis due to potential escalation triggered by fires can be identified by using Heat Flux Exceedance Curves (HFECs). The mechanical integrity of these can be evaluated in detail via the proposed Dynamic Thermal Stress Analysis (DTSA) by using the wall segmentation approach implemented in SuperChems™ **[19]**. While the method is detailed and accurate, it is also less expensive than other more time-consuming methods such as finite element analysis. The proposed approach is valuable for estimating the actual TTF and for conducting sensitivity analysis when considering key potential active and passive protections to be implemented:

- Optimization of the emergency relief system size
- Definition of the activation time and size for an emergency depressuring valve
- Minimum insulation thickness and material properties to be considered (i.e., thermal conductivity, heat capacity)
- Minimum required cooling load and duration if sprinkler systems are considered to be installed
- Development of specific emergency plan procedures

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