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A Risk-Based Approach for Predicting Domino Effects Due to Fires Combining Exceedance Curves with Dynamic Thermal Stress Analysis

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This article proposes a risk-based method for domino effect characterization and potential escalation for process equipment affected by thermal radiation (i.e., fires). This methodology intends to answer two key questions: (1) which process equipment is impacted by a heat flux capable of resulting in escalation due to equipment failure; and (2) what is the associated time to the process equipment failure; that is, Time to Failure (TTF). The first phase consists of developing dedicated heat flux exceedance curves for a given location of interest. The second phase involves a dynamic simulation for the prediction of the TTF due to fires impacting the equipment identified in phase one. A two-step approach is proposed for ensuring accurate results: (1) vessel wall segmentation to determine how the Ultimate Tensile Strength (UTS) of the material decreases as a function of temperature, and (2) the UTS is then compared with the Hoop stress by considering the equipment internal pressure combined with the installed overpressure protection performance.

This article defines step-by-step how to conduct a risk-based assessment and determine the TTF using a case study. It demonstrates the applicability and accuracy of this approach, which helps the decision-making process on how potential mitigation measures can be implemented. © 2017 American Institute of Chemical Engineers Process Saf Prog 000: 000–000, 2017

Keywords: domino effect; escalation; fire; boiling liquid expanding vapor explosion; exceedance curve; quantitative risk assessment; pressure relief device

INTRODUCTION

Three concepts have to be clearly understood when assessing an incident with domino effects: (1) primary event, (2) secondary target, and (3) secondary scenario. A primary event is defined as the accident scenario of concern, and its final outcomes are expressed in terms of physical effects; for example, thermal radiation, overpressure, and so forth. Secondary targets are equipment items that may be damaged by the primary event and, if damaged, the associated secondary scenarios have the potential to cause additional outcomes escalating the primary event, that is, the domino effect.

Fire assessments addressing escalation can be performed by following two different approaches: (1) a consequence-based approach that only considers the worst credible event, or (2) a risk-based approach that considers both the consequence and the frequency values that characterize the associated risk level. This article considers the risk-based approach and assumes that a complete Quantitative Risk Assessment (QRA) has been previously completed.

Process equipment impacted by fires can be identified through the development of exceedance curves that are based on QRA results. Furthermore, if the identification is based on the process equipment being impacted by a heat load high enough to cause domino effects, it can be selected for a more detailed analysis. This selection has to be based on worldwide recognized criteria when considering acceptable risk levels and heat load values capable of triggering escalation phenomena.

Once secondary targets are identified, a dynamic thermal stress analysis (DTSA) and a wall segmentation approach are proposed for determining the Time to Failure (TTF) of the equipment. The TTF provides the time between the fire starting and the predicted vessel rupture due to the fire hazard. Calculation of TTF provides guidance for: (1) the decision-making process on how potential mitigation and emergency response measures can be implemented, and (2) which are the remaining process conditions at the system for accurately estimating consequences of secondary scenarios.

EXCEEDANCE CURVES AND SPECIFIC DOMINO EFFECT CRITERIA

The exceedance curve approach was developed following the issue of the 2003 version of the Chemical Industries Association (CIA) guidance [1] and is widely used for facility siting studies. Exceedance curves can be used as a probabilistic description of the potential for a target location to experience various levels of effects; that is, heat radiation from fires, overpressure from explosions, and concentrations from flammable and/or toxic dispersions. An exceedance curve correlates the cumulative frequency of occurrence with any given parameter being exceeded; for example, heat flow received by fires. When addressing fires, the exceedance curve construction takes into account all identified fires that impact the secondary equipment under analysis. Furthermore, the specific exceedance heat flux value that impacts the secondary equipment is identified for each fire. As a result, as more heat flux values (i.e., end-points) are

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Table 1. Fires evidencing escalation based on heat load received by the target.

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.
Table extracted from Ref. 4.
Q_{HL} in [kW·m^{-2}]: Thermal Flow received by the fire.

evaluated during the consequence modeling phase of the QRA development, more accurate information is available for constructing exceedance curves. The following steps are required for constructing exceedance curves:

- Identify the exceedance heat flux level of each impacting fire (e.g., 35 kW·m^{-2}). This information is available based on the previous associated QRA results.
- Identify the individual frequency of occurrence of each impacting fire (e.g., 1.50 E −05 yr^{-1}). This information is based on the previous associated QRA results.
- Sort the exceedance heat flux levels for each impacting fire in descending order.
- Calculate the cumulative frequency of all fires that impact the receptor at the same exceedance heat flux level; that is, add the individual frequencies of all fires that impact the receptor with the same exceedance heat flux level to determine the cumulative frequency.
- Calculate the final cumulative frequencies at each specific exceedance heat flux level as follows: the cumulative frequency associated with the highest heat flux level is added to the cumulative frequency at the next lower heat flux level. This procedure is repeated n times, where n is the number of different heat flux levels, ensuring that the cumulated frequency at the lowest heat flux level comprises individual frequencies of all outcomes that impact the receptor.

When addressing domino effects and escalation triggered by fires, the exceedance curve approach allows for the identification of secondary equipment being impacted at a certain cumulative frequency of occurrence and at a certain heat flux level of interest. Therefore, it is important to acquire criteria for defining these two key threshold parameters when conducting domino effect analysis: the maximum tolerable cumulative frequency of occurrence threshold and the minimum heat flux threshold that leads to vessel failure:

- Maximum cumulative frequency of occurrence threshold; which is considered acceptable, and which has to be supported by well-known worldwide risk tolerability criteria, internal corporate guidelines, and/or recognized good engineering practices and standards; for example, 1.00 E −04 yr^{-1}, 5.00 E −05 yr^{-1}.
- Minimum heat flux threshold leading to escalation. The severity of fires (i.e., heat flux level) impacting on a target equipment is a critical issue that influences the dynamic temperature profile of involved vessels and the phenomena that may eventually lead to vessel failure. Cozzani et al. [2–4] conducted research which confirmed that despite the large number of possible fire events, few categories of industrial fires were relevant for escalation leading to domino effects. Accordingly, Table 1 provides guidance on minimum heat load values that could be considered for escalation analysis as a function of type of fire and secondary equipment characteristics.

Once the two threshold values are known, it is straightforward to use exceedance curves to identify secondary equipment that is subject to domino effect failure. For example, if a pressure vessel receives a heat flux greater or equal to 40 kW·m^{-2} from open pool fires at the given cumulative frequency threshold, the equipment will be selected for further analysis, and the equipment structural response analysis of the equipment will be performed to estimate the TTF; that is, time to effective mitigation. Otherwise, the equipment will be disregarded. Note that the TTF is the key parameter for evaluating the available time lapse between the start of the primary fire and the subsequent catastrophic failure of the impacted equipment.

DYNAMIC THERMAL STRESS ANALYSIS AND WALL SEGMENTATION APPROACH

This section proposes a methodology to accurately calculate the equipment TTF by combining a detailed DTSA and a wall segmentation approach. The proposed method is based on the fundamental heat transfer equation (Eq. 01) illustrated in the last revision of the API Standard 521 [5]:

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

The first term ($\alpha_w \varepsilon_f \sigma T_f^4$) is the flame radiative heat flux into the external wall or insulation surface. The second term ($h\left(T_{f,g} - T_{w,t}\right)$) is the hot combustion gases' convective heat flux into the external wall or insulation surface. Finally, the third term ($\varepsilon_w \sigma T_{w,t}^4$) is the heat flux that is reradiated by the external wall or insulation surface [6].

When SI units are used, $\boldsymbol{q_w}$ is the net heat flux reaching the wall or insulation surface in $W \cdot m^{-2} \cdot K^{-1}$, α_w is the external wall surface or insulation absorptivity, $\boldsymbol{\varepsilon_f}$ is the flame surface emissivity, σ is the Stefan–Boltzmann constant (i.e., 5.67 E −08 $W \cdot m^{-2} \cdot K^{-4}$), $\boldsymbol{T_f}$ 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 for the variables in **Eq. 01** are provided by the API Standard 521 [5] and Melhem [6].

Equation 01 illustrates that the heat load from a fire 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 the heat is transferred into the liquid and vapor contents. The vessel wall temperature increases and consequently the internal fluid temperature rises. As a result, the Ultimate Tensile Strength (UTS) of the vessel's material of construction decreases.

Additionally, the internal pressure rises (and therefore the hoop stress in the vessel walls) 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 in the region wetted by the liquid remains near the liquid temperature based on the high rate of heat transfer between the liquid and the vessel wall.

Heating rates caused by total pool fire engulfment, partial engulfment, or thermal radiation (i.e., pool fire exposure from a distance) will depend on the fuel type, burning rate, pool diameter size, flame height, flame title, flame drag, atmospheric transmissivity, and geometric view factor. A typical average fire flux associated with a C7 hydrocarbon pool fire is on the order of 60 $kW \cdot m^{-2}$. Lighter hydrocarbon pool fires, especially LNG fires can produce more intense heating with peak fire flux values well in excess of 250 $kW \cdot m^{-2}$. Most of the heat absorbed into the vessel contents is absorbed by the liquid because of the poor natural convection heat transfer between the vapor contents and the vapor walls. Typical failures will occur at the vapor/liquid interface because of increased thermal stress due to the difference in temperature between the vapor space hot metal and liquid space cooler metal [6].

Flame jet impingement causes high intensity localized heating. Because jets are efficient mixers, the wall impinged area can receive a fire flux as high as 350 $kW \cdot m^{-2}$. As the intense heating occurs and continues, the exposed local metal area thins. A thinner metal is weaker and ultimately the metal thins to a point where the exposed area starts to tear. Depending on the vessel contents pressure and temperature, and the extent of the tear, a Boiling Liquid Expanding Vapor Explosion (BLEVE) can occur and can be immediately followed by a fireball and vapor cloud explosion (VCE). Failures caused by flame jet impingements on the vapor space (no liquid) typically occur within a few minutes, on the order of 5 min [6]. The fire heat load is one of the key parameters that impacts the duration between the fire starting point and the eventual equipment failure leading to a Loss Of Containment (LOC) scenario. This time lapse can be as small as a few minutes (e.g., flame jet impingement causing 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). Thus, this time lapse is an important parameter to be calculated for the protection and prevention of escalation triggered by fire exposure (i.e., the domino effect) [4]. Note that Ref. 4 provides a state-of-the art review of heat radiation effects and associated escalation for equipment exposed to fires.

The accurate prediction of the conditions at the TTF provides 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 how severe the associated impacts are; that is, 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 multiphase 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 dynamics models also include incoming and outgoing fluid streams, to connect a particular 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, subcooled liquid flow, and multiphase flow with/without slip [7].

In SuperChems™ Expert [8], to account for detailed vessel wall and fluid heat transfer dynamics, the simulated equipment is segmented into multiple zones, as shown in Figure 1. This wall segmentation approach is based on dividing the equipment into multiple segments for close examination of the fluid dynamics and vessel wall thermal effects. Other valuable applications of the segmentation approach include

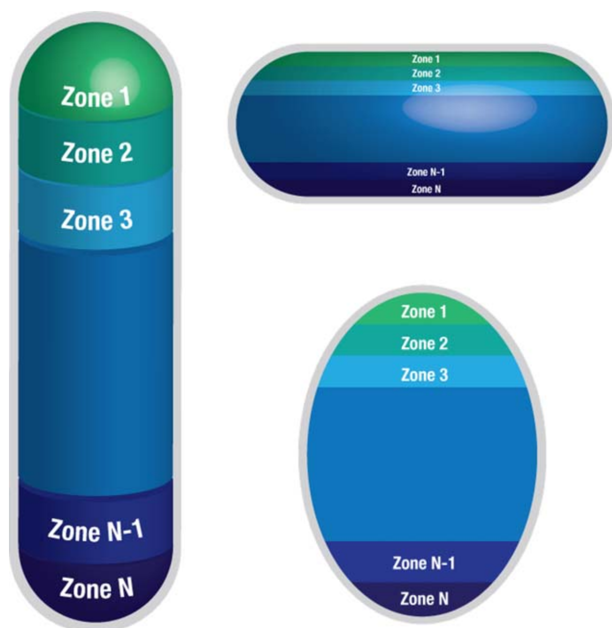

Figure 1. SuperChems™ Expert [8] segmentation scheme. [Color figure can be viewed at **wileyonlinelibrary.com**]

the modeling of external fire, localized heating, and flame jet impingement.

Once segmentation is defined, heat transfer analysis options are identified for each wall segment zone. 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 wall segment to fluid heat transfer 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 Eq. 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; however, it is possible to define fixed values for the heat transfer coefficients. The cited dynamics codes allow the user to specify vessel internals, which result in heat transfer and surface adsorption reactions.

When considering the installation of emergency relief systems in process equipment, it is also 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 [9].

Vessel flow models estimate the liquid swell and degree of vapor-liquid disengagement as a function of vapor throughput. 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. These vessel flow models implemented in SuperChems^{TM} Expert [8] 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.

Using the wall segmentation approach, the metal wall segment temperatures and the pressure histories are evaluated as a function of time. As a result, it is possible to then estimate the internal hoop stress and the UTS of the metal segments as a function of time and temperature.

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.

For example, a BLEVE is a potential outcome. Upon vessel failure, the sudden expansion and/or flashing of the vessel contents create 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 on the superheat available for bubble nucleation. Large depressurization rates can lead to large undershoots and thus, large bubble nucleation superheating. 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.

Assuming that the vessel contents undergo isentropic expansion, the total amount of internal available energy stored in the superheated liquid and/or the vapor can be calculated [7]. 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) subtracted by the Pressure-Volume (PV) work done on the atmosphere due to volumetric expansion (blast wave energy). Accordingly, the prediction of the system's process conditions at the TTF allow for accurate estimates of the impact distances of potential outcomes; for example, characterization of BLEVEs.

CASE STUDY

Baseline Simulation

After completing the risk-based quantitative assessment of a process facility, all pool fire outcomes were identified, filtered, and collected from LOCs defined during the QRA development. Each pool fire-outcome individual frequency of occurrence was estimated, and impact distances predicted at different selected heat flux values of interest were modeled using SuperChems^{TM} Expert [8].

Heat Flux Exceedance Curves were developed for four (4) pieces of equipment located in an area susceptible to be impacted for several pool fires (see Figure 2). A target frequency of occurrence of 1.00 E-04 yr^{-1} was selected based on a given risk tolerability threshold for identifying equipment potentially impacted by fire escalation. Additionally, the corresponding heat flow received from the primary fire was identified for each piece of equipment. Finally, if the heat flow was identified to be lower than the minimum value considered for escalation (e.g., 40 $kW{\cdot}m^{-2}$ from pool fires impacting pressurized equipment, based on Table 1), the potential for domino effect was disregarded. According to Figure 2, only Equipment 01 was identified with the potential for escalation triggered by fires, and the TTF was decided to be quantified with the aim to predict the available time for mitigation.

Tables 2 and 3 list the minimum required data for simulating the system via the DTSA proposed approach. Figures 3–5 illustrate the main results of the dynamic simulation.

The case study considers a process vessel exposed to a 2-h pool fire. The Pressure Relief Device (PRD) is sized such that the maximum pressure in the vessel reached during the fire is less or equal to 1.21 × Maximum Allowable Working Pressure (MAWP). Based on Figure 3, the pressure history confirms that the pressure in the vessel based on the heating rate absorbed by vessel contents is expected to stay below 1.21 × MAWP. While this is currently an acceptable practice, it is well known that a PRD cannot protect a vessel from failure for an extended fire duration. A properly sized PRD has to reseat and if the fire continues the vessel will ultimately fail at the reseat pressure of the PRD.

With the aim to analyze the vessel wall temperature dynamics, the vessel is divided into five segments. The temperature profiles for all five vessel metal segments are shown in Figure 4. As expected, the walls in contact with the vapor space become hotter than the walls in contact with the liquid

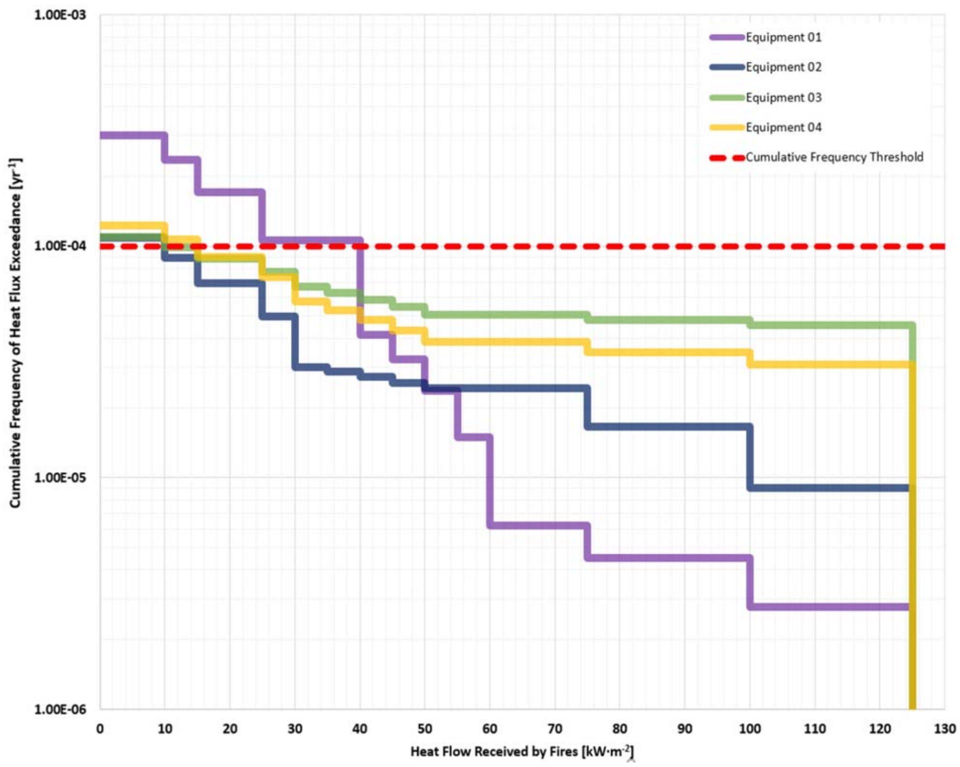

Figure 2. Heat flux exceedance curves for four [4] selected process equipment—pool fires. [Color figure can be viewed at **wileyonlinelibrary.com**]

Table 2. Vessel material UTS as a function of temperature.

Failure Stress Temperature [°C]	Failure Stress [atm]—2/3 UTS
20	2829.51
399	2632.12
482	2065.63
538	1658.03
593	1236.61
649	907.97
704	611.89
760	407.60

space. It can be observed that the liquid level is ultimately depleted (vaporized) and once the liquid level is depleted, the metal segments that become dry are heated more quickly. Note that it is also important to consider the impact of the onset of two-phase flow from a relief device. The heat stored in the vapor walls can ultimately be recovered by the vessel contents during the two-phase swell and/or flow since the vapor walls will get coated with a two-phase mixture.

Since the pressure history (Figure 3) and the metal wall segment temperatures (Figure 4) are known as a function of time, the internal hoop stress of the metal segments exposed to the fire can be estimated, and decide if the metal is likely to fail. This case study considers 2/3 of the UTS to be the failure boundary instead of 100%. A safety factor is normally recommended to account for uncertainties associated with metal properties, defects, and calculation methods [6]. The failure stress of each metal segment is shown in Figure 5 as is the internal hoop stress. This vessel is predicted to fail in approximately 33.4 min from the fire start. If there is sufficient fuel inventory to sustain a fire for this predicted TTF, the PRD is not going to protect the vessel from failure.

Even though the vessel's internal pressure during the fire is simulated by considering the action of a 3L4 relief device (whose characteristics are based on API Standard 526 [10]), it can be observed that an adequately sized pressure relief system is not enough to prevent the vessel failure due to fire exposure; that is, pressure in the vessel does not reach the Maximum Allowable Accumulated Pressure (MAAP) of the system, which is the MAWP of the system, 13.5 atm, plus 21% allowable accumulation based on API Standard 521 [5] for external fire exposure (Figure 3). Finally, if a vessel burst (e.g., BLEVE), a fireball, or a VCE outcome needs to be characterized, conditions at TTF provide the required input data for accurate consequence modeling.

Table 4 lists the estimated impact distances due to vessel burst at two (2) different TTFs; that is, TTF considered at 9 min, and predicted TTF at 33.4 min. Results confirm the importance of process conditions remaining in the system when the vessel is expected to fail.

Simulation with a Proposed Safeguard

Layers of protection should be considered to maximize the predicted TTF whenever the predicted TTF is considered insufficient for emergency responders to eliminate/mitigate the fire. For the example described above, 33 min may not be considered sufficient time. The installation of additional safeguards would prevent the catastrophic equipment failure and ensure the effectiveness of prevention measures of escalation caused by fire.

For example, one effective layer of protection that would increase the emergency response time would be fitting the

Table 3. Process equipment and scenario definition.

Parameter	Units	Value
Equipment Dimensions and Material of Construction		
Maximum Allowable Working Pressure, MAWP	[atm]	13.5
Design or limiting temperature	[°C]	550.00
Material of construction	[–]	SA-516-G70
Length (straight side for cylinders)	[m]	9.5707
Inside diameter	[m]	1.0135
Shell wall thickness	[m]	0.0159
Left and Right Head	[–]	Elliptical 2:1
Total Surface Area	[m^2]	32.699
Total Volume	[m^3]	7.9931
Number of Wall segments considered	[–]	5.0000
Initial Process Conditions		
Process Temperature	[°C]	95.5800
Process Pressure	[atm]	8.00000
Initial liquid level	[%]	85.0000
Mixture Composition – Component 01: PROPANE	[% mass]	0.06110
Mixture Composition – Component 02: n-BUTANE	[% mass]	0.16110
Mixture Composition – Component 03: n-PENTANE	[% mass]	0.30000
Mixture Composition – Component 04: HEXANE	[% mass]	0.47780
Fire Properties		
Heat Load predicted by using Exceedance Curve/criteria	[$kW{\cdot}m^{-2}$]	40.0000
Flame and Gas temperature (Iteration Eq. 01)	[°C]	1050.00
Initial Convective Heat Transfer Coefficient	[kW·m$^-$2·°C^{-1}]	1.96E-02
Fire properties: Emissivity and Absorptivity	[–]	0.75000
Relief System Properties		
PRD size based on API Standard 526 [10]	[–]	3L4
PRD Set Pressure	[atm]	13.5000
PRD Reseat Pressure	[atm]	12.5550

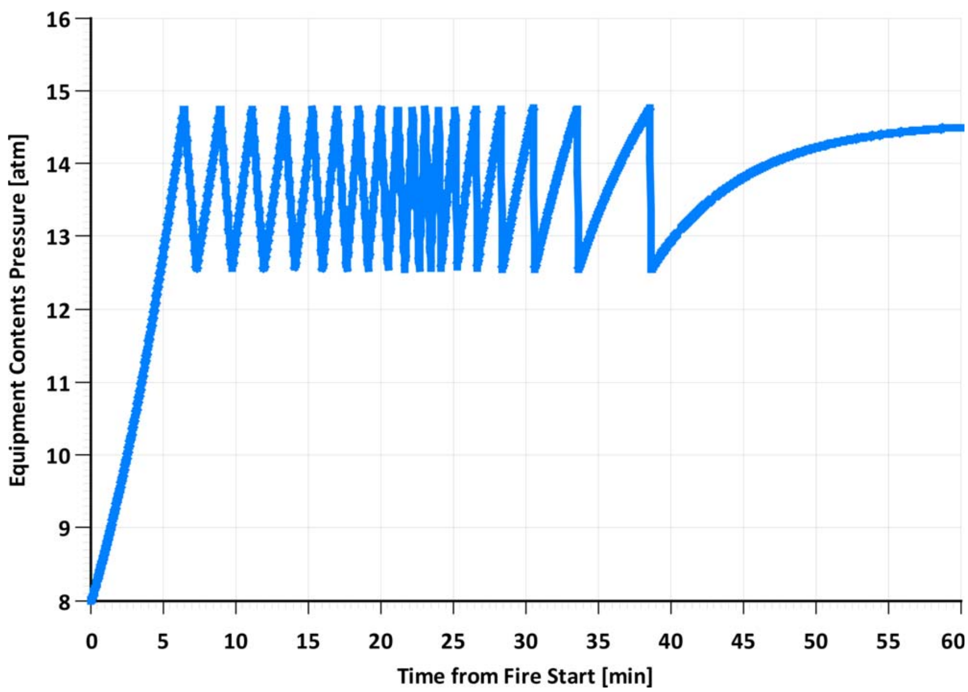

Figure 3. Pressure history. Source: SuperChems™ Expert [8]. [Color figure can be viewed at **wileyonlinelibrary.com**]

vessel with fire-proof insulation. Fire-proof insulation can ensure the mechanical integrity of the equipment exposed to fire for a period of time in which emergency response is possible and effective.

Figures 6–8 illustrate the results of a dynamic simulation of the system under analysis after considering the installation of one (1) inch thickness of fire-proof insulation (i.e., mineral wool) that is properly jacketed and banded to the

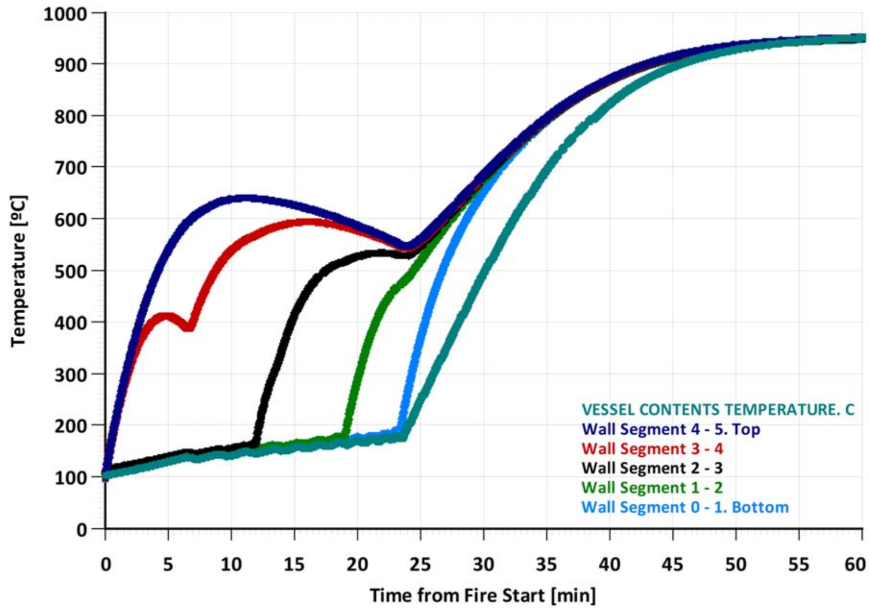

Figure 4. Wall segments temperature profile. Source: SuperChems^{TM} Expert [8]. [Color figure can be viewed at **wileyonlinelibrary.com**]

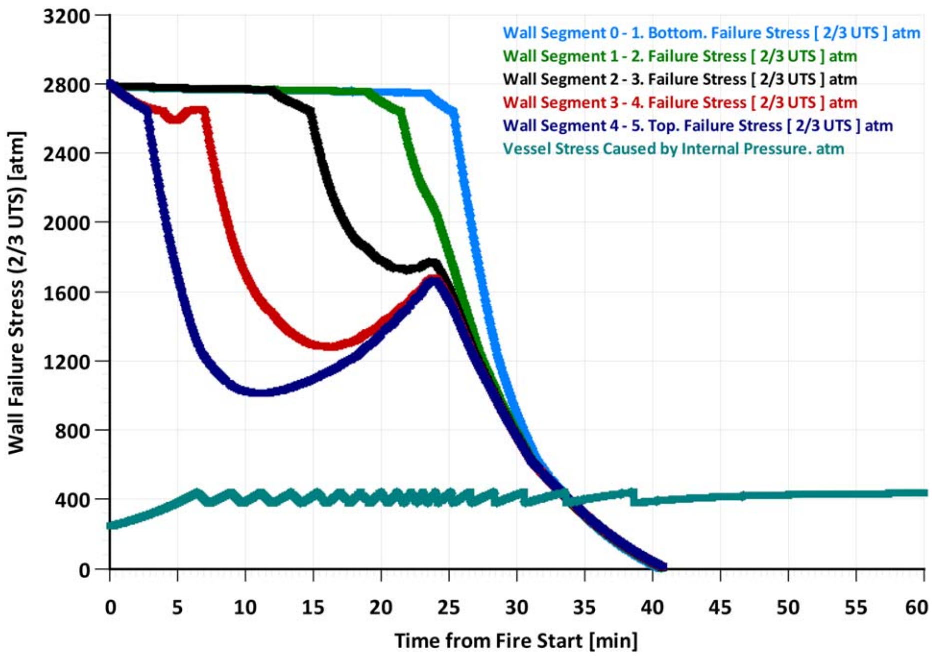

Figure 5. Wall segments stress profile. Source: SuperChems^{TM} Expert [8]. [Color figure can be viewed at **wileyonlinelibrary.com**]

equipment. Note that the insulation heat capacity and thermal conductivity is considered as a function of temperature and used to refine the reduced heat transfer between fire and equipment walls (see Table 5 for specific information of mineral wool).

Based on results illustrated in Figures 6–8 (i.e., pressure history, wall segments temperature, and stress profiles), it can be observed that the addition of one (1) inch of jacketed and banded mineral wool insulation to the equipment under analysis is sufficient to ensure its mechanical integrity during the first two (2) hours after the fire start, which may be considered sufficient time to mitigate the contingency. As a result, it is confirmed that the combination of an adequate pressure relief system, and the installation of fire-proof insulation ensure the mechanical integrity of the system during a period of time which is considered sufficient to mitigate the escalation caused by fire.

BRIEF OVERVIEW OF THE SUPERCHEMS EXPERT^{TM} FLOW DYNAMICS MODELS

The case studies considered in this article were modeled using the commercial software package SuperChems^{TM}

Table 4. Vessel Burst Impact Distances.

	TTF - 9 [min]	TTF- 33.4 [min]
Mass Remaining in Vessel		
PROPANE [Kg]	149.06	0.474
n-BUTANE [Kg]	465.65	5.52
n-PENTANE [Kg]	948.18	28.715
HEXANE [Kg]	1587.3	94.344
Process Conditions Remaining at TTF		
Temperature [°C]	136.28	630.6
Pressure [atm]	14.64	14.63
Vapor mass [Kg]	53.65	129.05
Vapor volume [m^3]	1.43	7.99
Liquid mass [Kg]	3096.5	0
Liquid volume [m^3]	6.57	0
Total mass [Kg]	3150.2	129.05
Total volume [m^3]	7.99	7.99
Volume Full of Liquid [%]	82.14	0
Overpressure Threshold [atm]	**Impact distances - Vessel Burst [m]**	
0.07 (1 psia)	54.84	28.93
0.2 (3 psia)	29.26	15.43
0.34 (5 psia)	21.12	11.14
0.48 (7 psia)	17.17	9.06

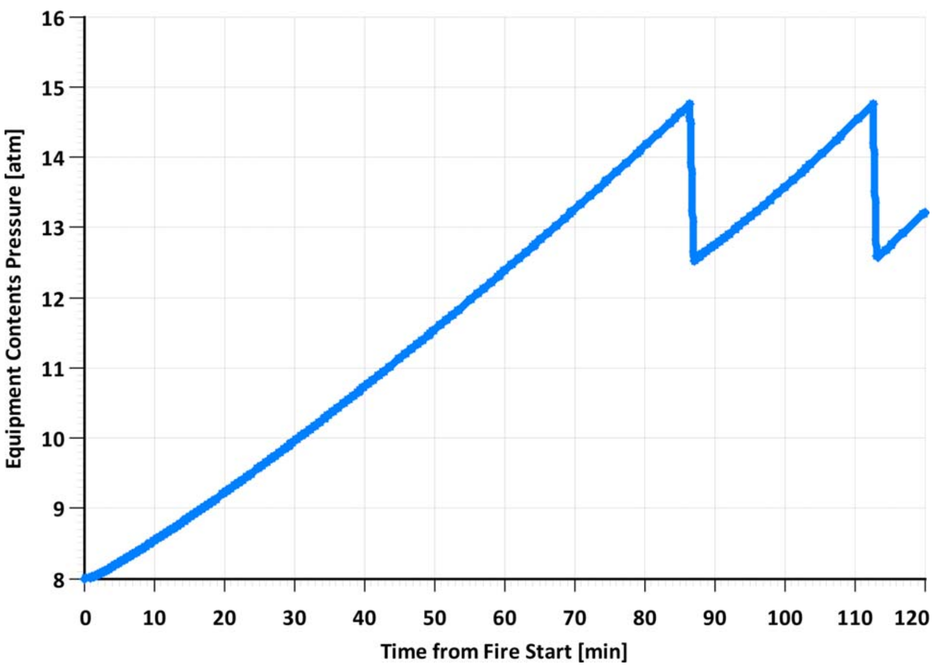

Figure 6. Pressure history—1 inch fire-proof insulation. Source: SuperChems™ Expert [8]. [Color figure can be viewed at **wileyonlinelibrary.com**]

Expert, a component of the ioMosaic Process Safety Office™ suite. SuperChems™ Expert solves the time-dependent detailed material, momentum, phase behavior, and energy balances for single and/or multiple interconnected vessels with complex piping for single and multiphase flow. Vapor/liquid disengagement dynamics, as well as reaction systems, are seamlessly handled for vessel and piping flow. The AIChE Design Institute for Emergency Relief Systems (DIERS) markets and sells SuperChems™ for DIERS (a subset of SuperChems™ Expert) that is capable of simulating all the case studies considered in this article. A unique aspect of the SuperChems™ computer code is how the vessels are segmented and connected (see Figure 1). There is no limit on the number of segments a user can specify. The ability to define multiple segments allows the modeling of flame jet impingement. A wide variety of vessel shapes and heads, including composite vessels, connectivity options, and relief and mitigation options, are easily represented.

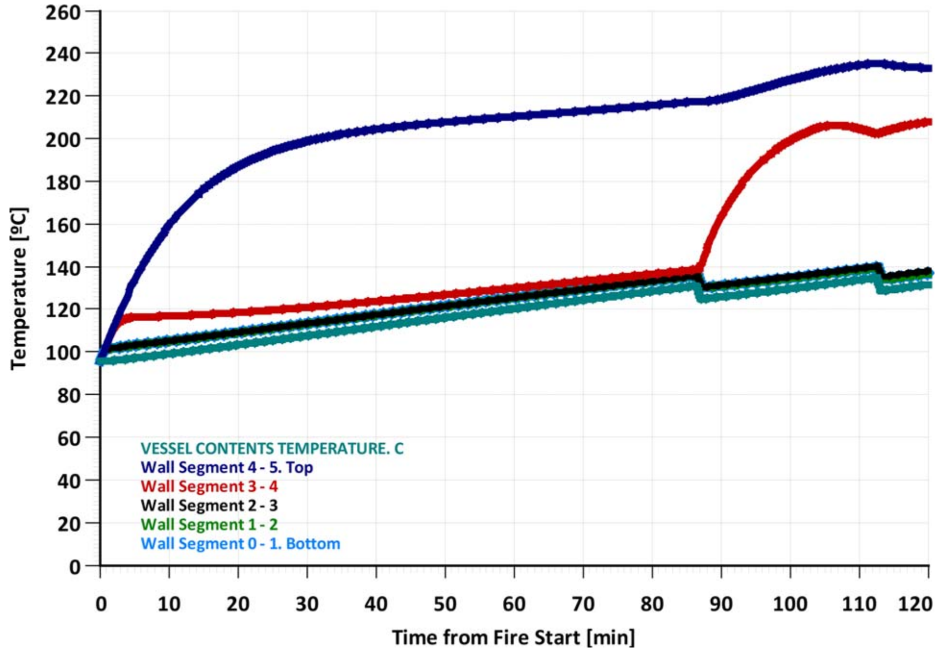

Figure 7. Wall segments temperature profile—1 inch fire-proof insulation.Source: SuperChems^{TM} Expert [8]. [Color figure can be viewed at **wileyonlinelibrary.com**]

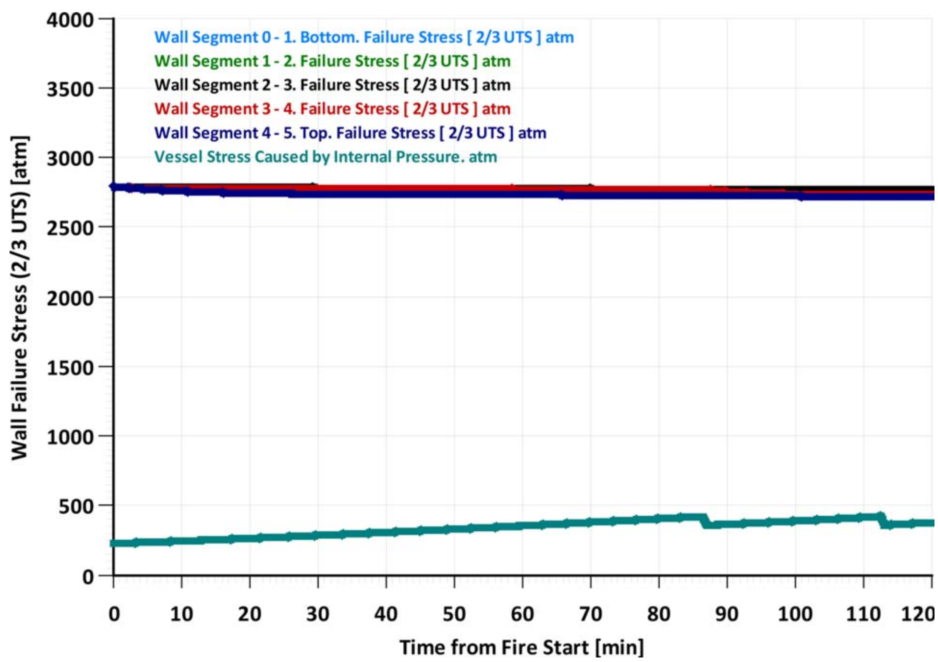

Figure 8. Wall segments stress profile—1 inch fire-proof insulation.Source: SuperChems^{TM} Expert [8]. [Color figure can be viewed at **wileyonlinelibrary.com**]

CONCLUSIONS

Exceedance curves can be used for the identification of process equipment that may be adversely impacted by industrial fires. Filtering all outcomes with the same fire classification (e.g., pool fires), and taking into account the topology of the target equipment under analysis, dedicated exceedance curves can be constructed for each identified process equipment. Once quantitatively identified, the process equipment that requires a more detailed analysis due to potential escalation (i.e., refer to Table 1 for specific criteria), can be evaluated in more detail by conducting the proposed DTSA and using the wall segmentation approach implemented in SuperChems^{TM} Expert [8].

This method is capable of accurately estimating the equipment TTF: parameter that helps safety professionals in the decision-making process. The proposed approach is less expensive and less time-consuming than other methods such as computational fluid dynamics.

Table 5. Mineral wool insulation properties.

Temperature [°C]	Specific Heat, C_p [J·kg^{-1}·°C^{-1}]	Thermal Conductivity, k [kW·m^{-1}·°C^{-1}]
37.78	836.80	5.80 E-05
93.33	836.80	6.20 E-05
148.89	836.80	6.70 E-05
204.44	836.80	7.20 E-05
260.00	836.80	7.80 E-05
315.56	836.80	8.50 E-05
371.11	836.80	9.20 E-05
426.67	836.80	1.01 E-04
482.22	836.80	1.11 E-04
537.78	836.80	1.23 E-04

*Mineral Wool density @ 25°C; [kg·m^{-3}]: 63.993.

The following can be concluded from a detailed characterization of an equipment exposed to external fire:

- An adequate pressure relief valve does not ensure the mechanical integrity of a system under fire exposure, and additional mitigation measures may be required to prevent escalation of the fire event.
- The size of the selected PRD has a direct impact on the predicted vessel TTF and conditions remaining in the system. An optimum PRD size can be achieved via sensitivity analysis with the aim to maximize the TTF or minimize associated impacts due to vessel failure. Furthermore, the PRD size needs to be sufficient so that the pressure inside the vessel is below the MAAP.
- Effective additional mitigation measures include installation of depressuring valves, fire-proof insulation, and water sprays. Each of these mitigation options can be accurately modeled to determine their effectiveness.
- If the TTF or time to mitigation is greater than the fire duration, then emergency response time is sufficient and decision makers can decide whether additional safeguards need to be implemented or not.
- Conditions predicted at TTF favor more accurate consequences and risk estimations due to more detailed information related to TTF conditions (i.e., mass remaining in the system, mixture composition, pressure, and temperature). The consequence modeling and predicted effects due to equipment catastrophic potential outcomes can then be considered for inclusion in dedicated domino effects and escalation analyses.

The proposed approach can be considered the starting point for a sensitivity analysis. The following four (4) parameters can influence the prediction of TTF, associated available internal energy in the system, and thus, the potential for domino effects and escalation:

- 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 for sprinkler systems

LITERATURE CITED

1. CIA, Guidance for the Location and Design of Occupied Buildings on Chemical Manufacturing Sites, Chemical Industries Association, London, ISBN 1858970776, 2003.
2. V. Cozzani, G. Gubinelli, and E. Salzano, Escalation thresholds in the assessment of domino accidental events, J Hazard Mater 129 (2006), 1–21.
3. V. Cozzani, G. Gubinelli, and E. Salzano, "Criteria for the escalation of fires and explosions," Proceedings of the 7th Process Plant Safety Symposium, American Institute of Chemicals Engineers, New York, NY (2006), p. 225.
4. G. Reniers and V. Cozzani, "Domino effects in the process industries," Modeling, Prevention and Managing, Elsevier, Amsterdam (2013).
5. API, API Standard 521 – Pressure Relieving and Depressuring Systems, 6th Ed., Washington, DC, 2014.
6. G.A. Melhem and D. Gaydos, Properly calculate vessel and piping wall temperatures during depressuring and relief, Process Saf Prog 34 (2015), 64–71.
7. G.A. Melhem, Advanced Consequence Analysis; Fluid Flow, Emergency Relief Systems Design, Thermal Hazards Assessment, Emission, Dispersion, Fire and Explosion Dynamics, ioMosaic Corporation, 2006.
8. ioMosaic Corporation, SuperChems Expert™, component of Process Safety Office™, ioMosaic, Available at: **http://www.iomosaic.com/software/process-safety-office-**.
9. H.G. Fisher, H.S. Forrest, S.S. Grossel, J.E. Huff, A.R. Muller, J.A. Noronha, D.A. Shaw, and B.J. Tilley, Emergency Relief System Design Using DIERS Technology, The Design Institute for Emergency Relief Systems (DIERS) Project Manual, AIChE, New York, 1992.
10. API Standard 526, Flanged Steel Pressure Relief Valves, 5th Ed., American Petroleum Association, Washington, DC, 2002.