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Risk-Based Approach - Domino Effect and Escalation Triggered by Fires

Combining Dynamic Thermal Stress Analysis and Wall Segmentation Approach

An ioMosaic White Paper

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Abstract

Escalation and Domino Effect triggered by fires is a well-known phenomenon that has caused past severe accidents in the process industry. This paper proposes a risk-based approach for domino effect analysis by combining Exceedance Curves (ECs) with Thermal Stress Dynamic Analysis (TSDA). ECs such as Heat Flux Exceedance Curves (HFECs) are constructed and used for the identification of target equipment that may be impacted by heat flow received from primary industrial fires. Given a target frequency, the corresponding thermal flow is identified and can be used to screen equipment from further consideration. Otherwise, further analysis is conducted to estimate the Time to Failure (TTF), which is the available time for mitigation. A case study is developed for illustrative purposes. Additionally, the effectivity of certain mitigation measures such as fire-proof insulation is discussed and simulated to predict a new, longer TTF which allows more time to extinguish the fire and minimizes the possibility of escalation and domino effect due to fires.

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Introduction

Three concepts should be clearly understood when assessing a domino accident: (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 Secterms of physical effect such as thermal radiation or overpressure. 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 final outcomes escalating the primary event.

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 **[1]**. Detailed information on risk-based quantitative assessment development can be found in references **[1]**, **[2]**, **[3]**, **[4]**, **[5]** and **[6]**.

After the risk-based assessment is conducted, the results for thermal radiation are used to construct Heat Flux Exceedance Curves (HFECs) at a target location, which properly identify equipment impacted with a high thermal radiation at a cumulative frequency **[6]**. Based on the HFECs, the heat flux at certain cumulative frequency threshold is determined. If the heat flux impacting the target location is greater than a certain selected value for escalation, an advanced Dynamic Thermal Stress Analysis (DTSA) is conducted to calculate the Time to Failure (TTF) of the equipment. The TTF is the time between the fire start and the rupture of the vessel due to the fire.

Despite the large number of possible fire events, few categories of industrial fires are relevant for escalation leading to domino effect, such as jet fires and pool fires. Further explanation on the types of fires and damage criteria can be found in references **[4]** and **[7]**.

Table 01 classifies the different fires identified in the process industry, showing escalation criteria based on the heat load received by the target **[9]**.

Table 01: Fires Showing Escalation Based on Heat Load Received by the Target

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

Note 01: Flammable vapors ignition for floating roof tanks

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

Domino Effect Definition and Study Purpose

Exceedance Curve Methodology

The Exceedance Curve (EC) approach was developed based on the 2003 version of the Chemical Industries Association (CIA) guidance and is widely used for facility siting studies. Further information regarding the Exceedance Curves development can be found in references **[1]** and **[9]**. When addressing domino effect and escalation triggered by fires, the EC approach allows identifying specific equipment impacted at a cumulative frequency and heat flow threshold. To construct an EC to address thermal radiation (i.e., Heat Flow Exceedance Curves, HFECs), the same outcomes should be filtered by fire type (e.g., pool fires, jet fires) and the type of the target equipment (see the criteria in **Table 01**). The HFECs can be used to identify target equipment being impacted by a fire outcome of interest based on: (1) a cumulative frequency of interest and (2) a heat flow threshold of interest.

After the identification and selection of process equipment triggered by primary fires, the structural response of the equipment is performed to estimate the TTF, which is the time for effective mitigation. The TTF is the key parameter for estimating the time between the start of the primary fire and the subsequent catastrophic failure of the impacted equipment and is based on DTSA approach.

Thermal Stress Dynamic Analysis and Wall Segmentation Approach

Based on the HFECs, target equipment is identified at a certain cumulative frequency threshold. If the heat flow value is not greater than a certain threshold, such as40 $kW \cdot m^2$ for pool fires, no further analysis is required as escalation is not expected to occur. For damage criteria to equipment based on different types of fires, information can be found in reference **[4]**. Otherwise, additional analysis for the affected equipment needs to be conducted to identify the potential for domino effect and escalation. Criteria for domino effect and escalation due to fires based on well-known thresholds can be found in reference **[10]**; and criteria for domino effect due to explosions based on well-known thresholds and by Single Degree of Freedom (SDOF) analysis can be found in references **[11]** and **[12]**. Since fire is the primary event, an accurate model to predict the heat load due to fire is required.

This paper presents a methodology to calculate the equipment TTF by a detailed wall segmentation approach using the fundamental heat transfer equation illustrated in the latest revision of API-521 **[13]**. Criteria and further explanation on the proposed approach can be found in reference **[14]**.

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 defined Loss of Containment Scenarios (LOCs). Each pool fire outcome individual frequency was estimated and impact distances at different heat flux values were predicted from SuperChems™ **[15]**.

Heat Flux Exceedance Curves were developed for four pieces of process equipment located in an area vulnerable to several pool fires identified in the process unit (**Figure 01)**. A target frequency of 1.00E-04 yr^{-1} was the given risk tolerable threshold for identifying equipment potentially impacted by fire escalation. Additionally, the corresponding heat flow received by the primary fire was identified for each equipment. If the heat flow was lower than the minimum value considered for escalation (e.g., 40 $kW \cdot m^{-2}$ from pool fires impacting pressurized equipment, based on **Table 01**), the potential for escalation was discarded. According to **Figure 01**, only Equipment 01 was identified with potential for escalation triggered by fires and the TTF was quantified to predict the available time for mitigation. **Table 02** and **Table 03** provide the minimum required data for simulating the system by the DTSA proposed approach. **Figure 02**, **Figure 03** and **Figure 04** illustrate the main results of the dynamic simulation.

Table 02: Process Equipment Failure Stress Data

Failure Stress Temperature [ºC]	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

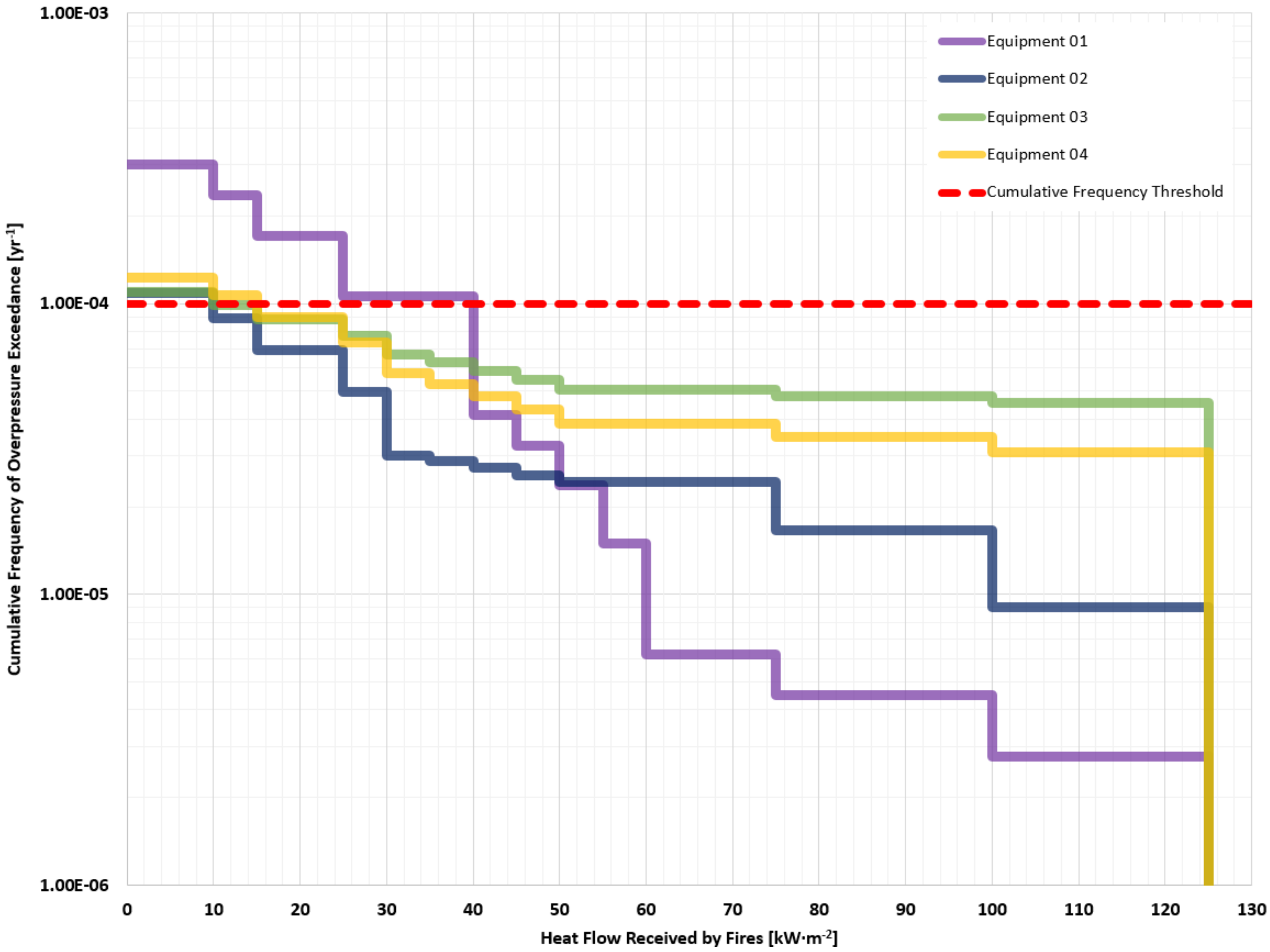
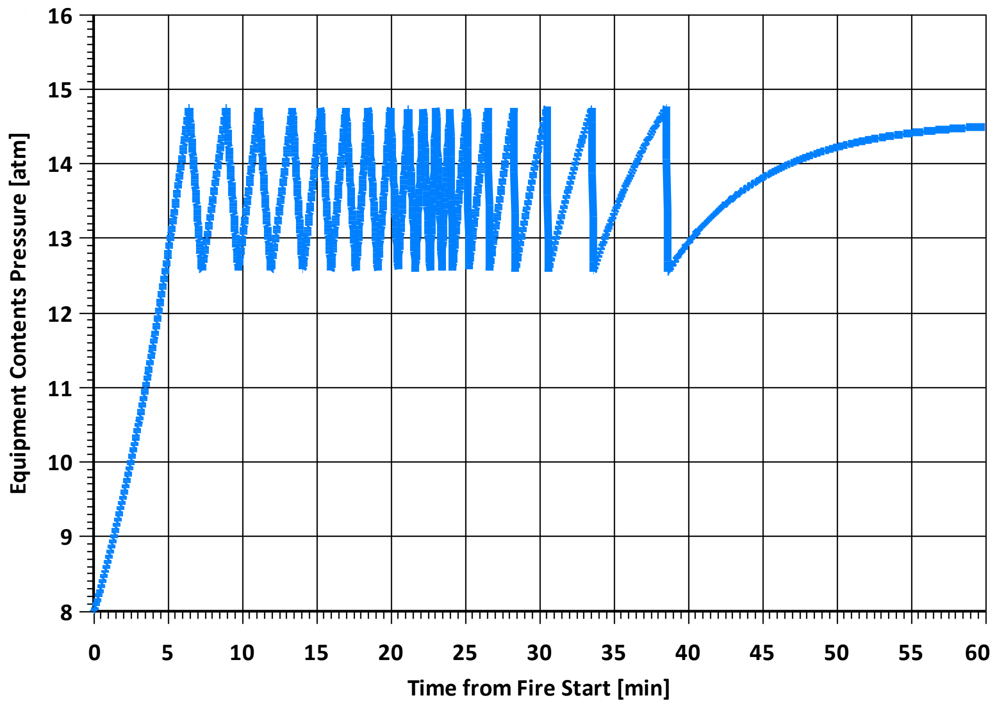


Figure 01: Heat Flux Exceedance Curves for Four Selected Process Equipment – Pool Fires

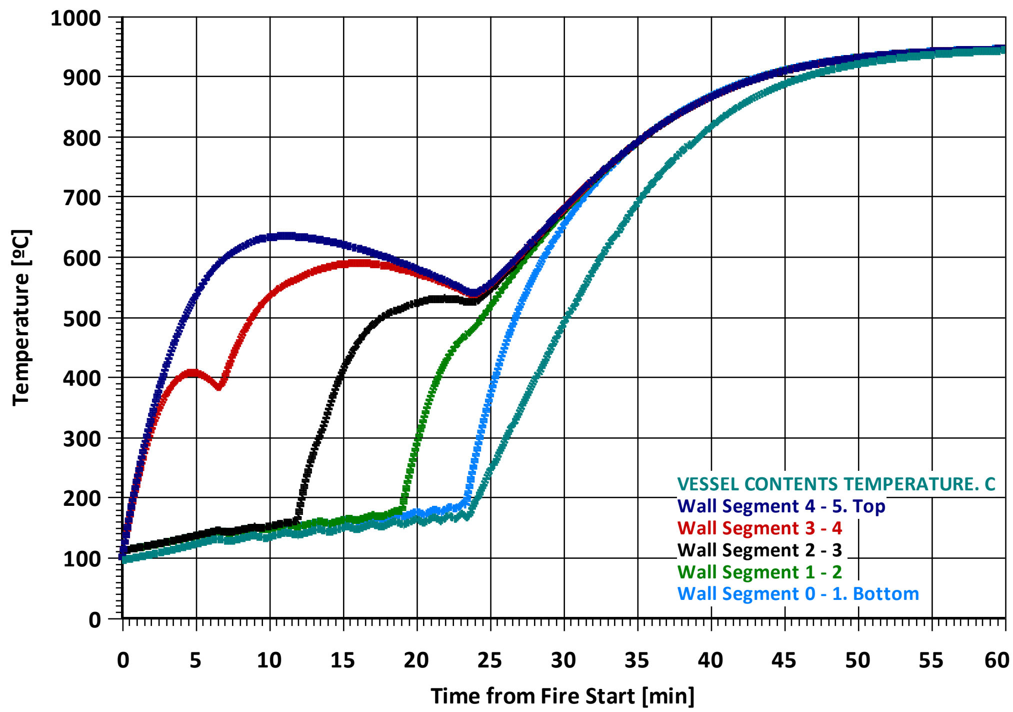
Table 03: Process Equipment and Scenario Definition

Parameter	Units	Value
Equipment Dimensions and Material of Construction		
Maximum Allowable Working Pressure, MAWP	[atm]	13.5
Design or limiting temperature	[ºC]	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	[ºC]	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 HFCEs	[$kW \cdot m^{-2}$]	40.0000
Flame and Gas temperature (Iteration **Equation 01**)	[ºC]	1150.00
Initial Convective Heat Transfer Coefficient	[$kW \cdot m^{-}2 \cdot {}^{o}C^{-1}$]	1.96E-02
Fire properties: Emissivity and Absorptivity	[-]	0.75000
Relief System Properties		
PSV size based on API STD 526 **[16]**	[-]	3L4
PSV Set Pressure	[atm]	13.5000
PSV Reset Pressure	[atm]	12.5550



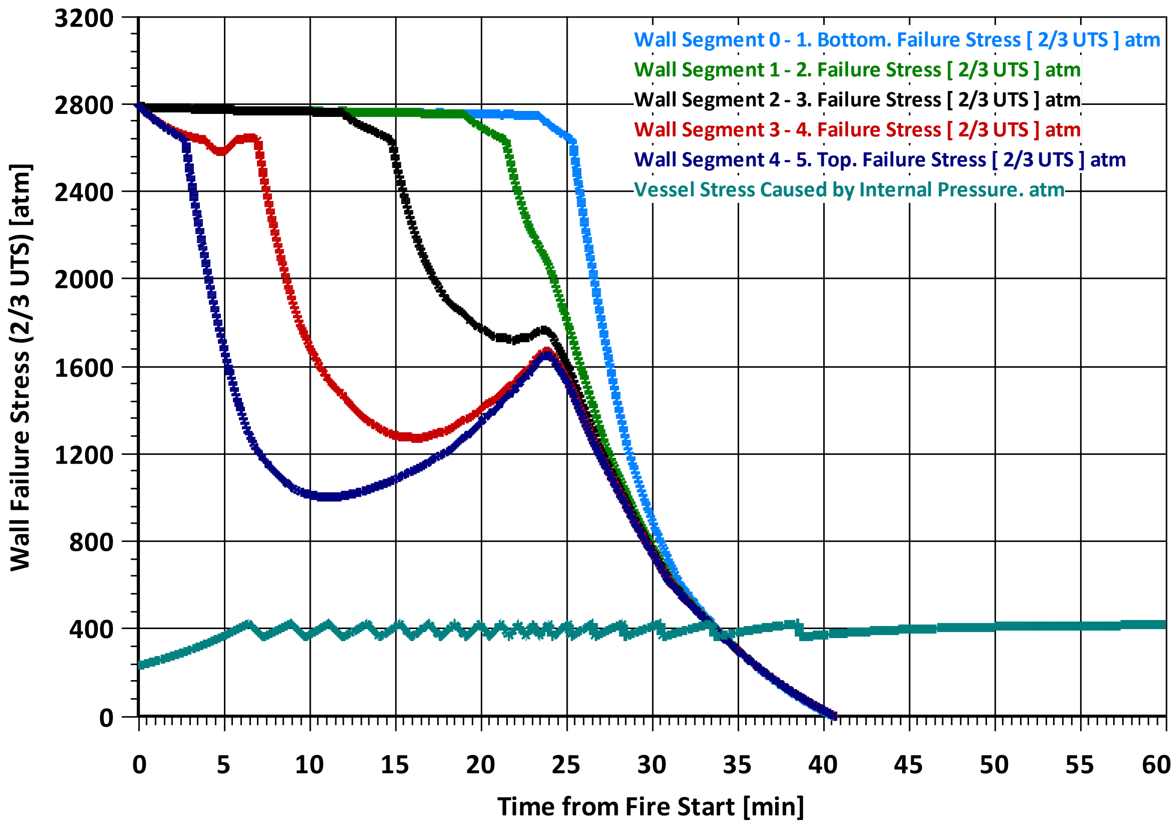
Source: SuperChems™ **[15]**

Figure 02: Pressure Profile



Source: SuperChems™ **[15]**

Figure 03: Wall Segment Temperature Profile



Source: SuperChems™ **[15]**

Figure 04: Wall Segments Stress Profile

Figure 04 illustrates the failure stress of each metal segment along with the internal hoop stress. The TTF is predicted when the wall tensile strength intersects the internal hoop stress. The analyzed process equipment is expected to fail after approximately 33 minutes from the fire start. Even though the system is simulated by considering a 3L4 relief device based on API Standard 526 **[16]**, a well-sized pressure relief system is not able to prevent the catastrophic vessel failure due to fire exposure. The pressure in the vessel does not reach the Maximum Allowable Accumulated Pressure (MAAP) of the system, which is the Maximum Allowable Working Pressure (MAWP) of the system, 13.5 atm, plus 21 percent allowable accumulation based on API Standard 521 **[13]** for external fire exposure.

Simulation with Risk Reduction Measures

Risk reduction measures should be considered to maximize the predicted TTF by providing enough reaction time for emergency response from the start of the fire, as 33 minutes is not considered to be enough time for adequate response. This would prevent the catastrophic equipment failure and maximize the effectiveness of prevention measures to minimize the risk of escalation caused by fire. One effective reduction measure is the installation of fire-proof insulation. After confirming the relief system provides sufficient relief and is stable, fire proof insulation can improve the mechanical integrity of the equipment when emergency response is possible and effective.

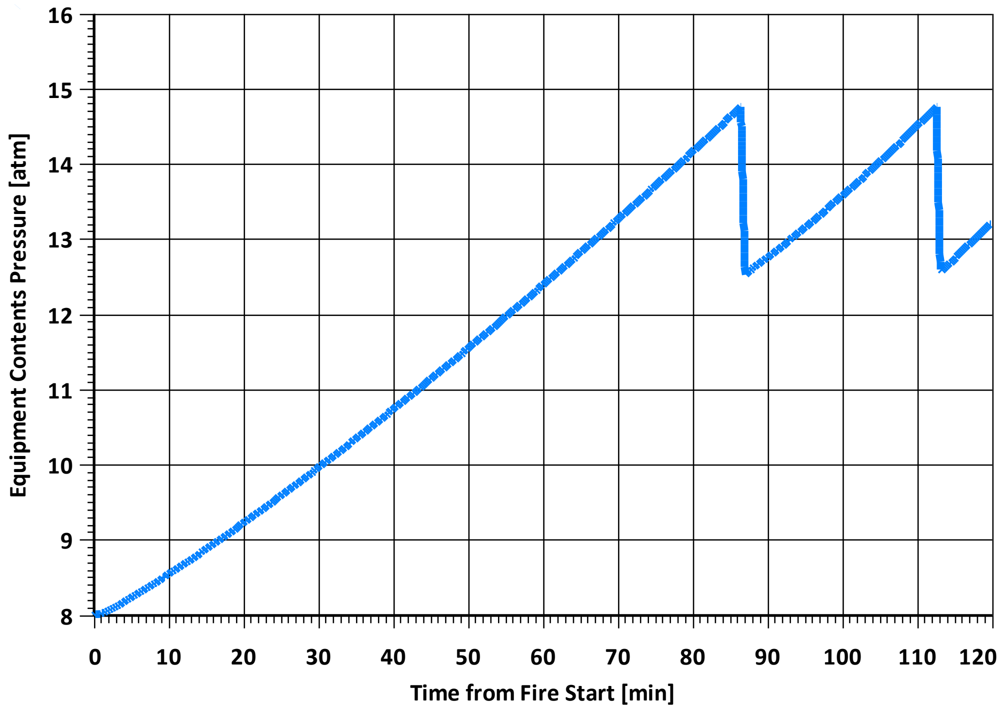
Note that the insulation heat capacity and thermal conductivity are considered as a function of temperature to refine the reduced heat transfer between fire and equipment walls (see **Table 04** for specific information of mineral wool).

Table 04: Mineral Wool Insulation Properties

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

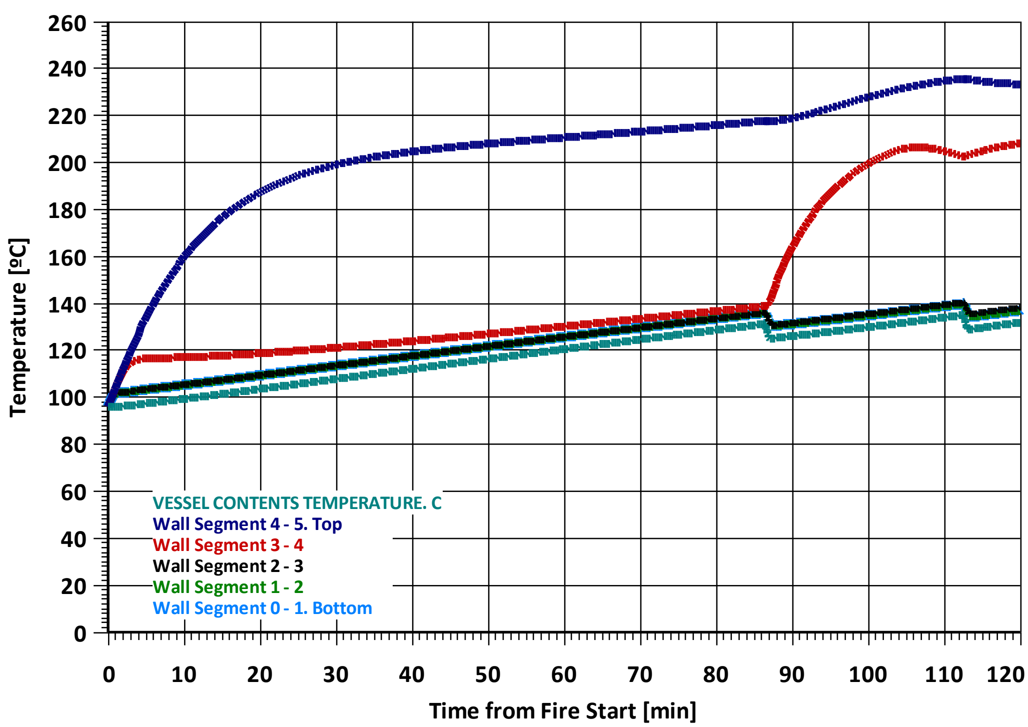
***Mineral Wool density @ 25ºC: 63.993 $kg \cdot m^{-3}$

Source: XXXXXXXXXX



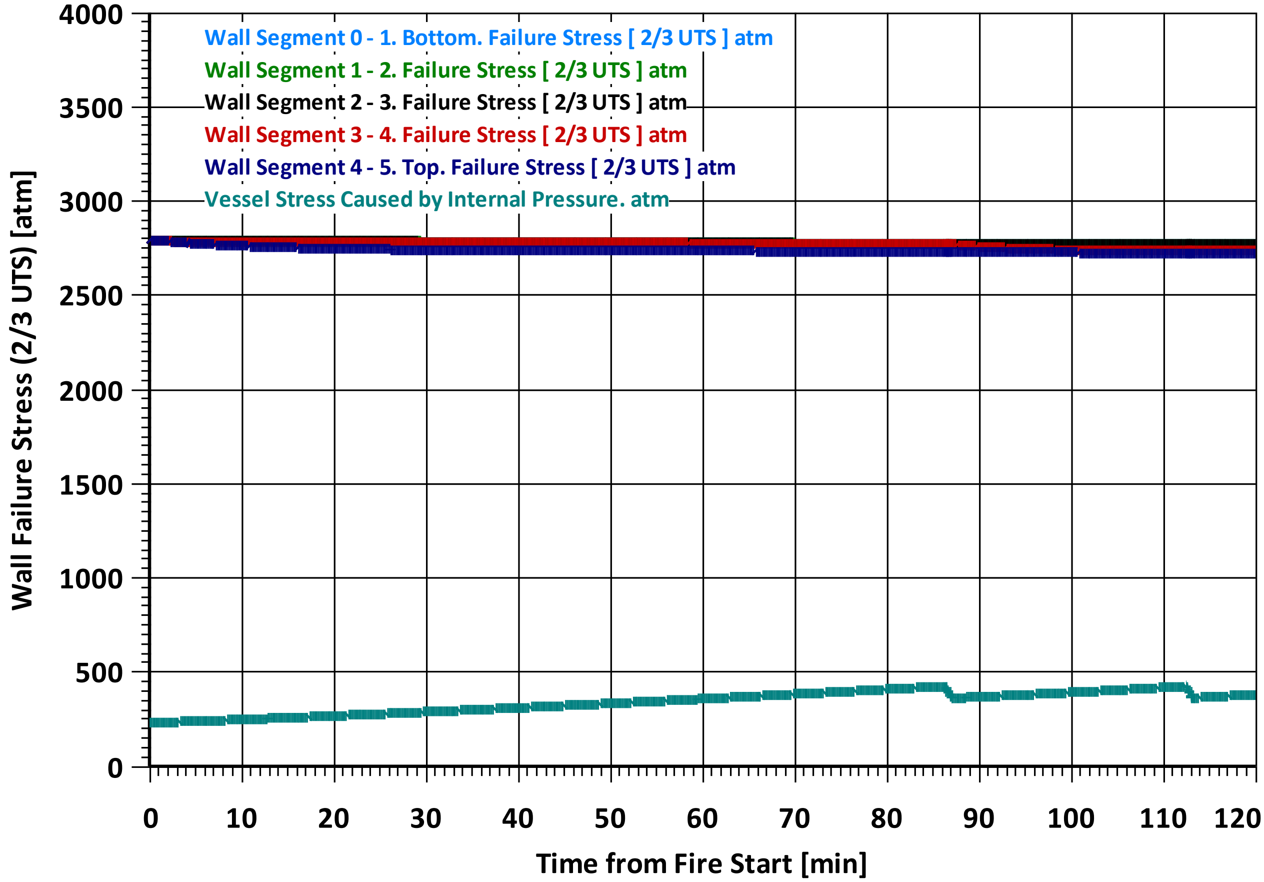
Source: SuperChems™ **[15]**

Figure 05: Pressure History – 1-inch Fire-Proof Insulation



Source: SuperChems™ **[15]**

Figure 06: Wall Segments Temperature Profile – 1-inch Fire-Proof Insulation



Source: SuperChems™ **[15]**

Figure 07: Wall Segments Stress Profile – 1-inch Fire-Proof Insulation

Based on results illustrated in **Figure 05**, **Figure 06** and **Figure 07**, it is confirmed that by adding 1 inch of mineral wool insulation to Equipment 01 is sufficient to enhance its mechanical integrity during the first two hours after the fire start, which is considered sufficient time to mitigate the contingency. These results confirm that the combination of an adequate pressure relief system and the installation of fire proof insulation are expected to enhance the mechanical integrity of the to mitigate the escalation caused by fire.

Conclusions

HFECs can be used for the identification of process equipment that may be impacted by heat flow received from primary industrial fires. Filtering all outcomes that entail the same fire classification (such as, pool fires) and considering the type of the target equipment, dedicated HFECs can be constructed for each process equipment. Thereafter, two criteria can be applied using HFECs:

- Given a thermal flow received from primary fires, the corresponding is identified. Based on pre-established criteria, if the frequency of occurrence is remote, the potential for escalation can be discarded. Otherwise, the equipment Time to Failure (TTF) is identified to predict the available time for mitigation by a structural response analysis.
  - ✓ Information on criteria for cumulative frequency and risk tolerability criteria can be found in reference **[6]**
  - ✓ Information on thermal flux criteria used to evaluate if domino effect and escalation is applicable can be found in reference **[4]**; Once quantitatively identified, process equipment requiring a more detailed analysis due to potential escalation can be evaluated by Dynamic Thermal Stress Analysis (DTSA) using the wall segmentation approach implemented in SuperChems™ **[15]**. This method is capable of accurately estimating the equipment TTF that assists decision makers in proposing mitigation options. The proposed approach is less expensive and time-consuming than other methods, such as finite element analysis. A case study has been fully developed and the following conclusions can be stated based on illustrated dynamic simulations.
- An adequate pressure relief valve does not safeguard the mechanical integrity of a system under fire exposure and additional mitigation measures may be required to be considered.
- The size of the selected Pressure Relief Device (PRD) has a direct impact on the predicted vessel Time to Failure (TTF) and conditions remaining in the system. An optimum PRD size can be achieved by sensitivity analysis to maximize the TTF or minimize associated impacts due to vessel failure. Furthermore, the PRD size needs to be sufficient such that the pressure inside the vessel is below the MAAP.
- Effective additional mitigation measures may include installation of depressuring valves, fire-proof insulation and/or water sprays.
- If the fire duration is limited, the TTF can allow for better decision making and emergency response.

- Conditions predicted at TTF favor more realistic consequences and risk estimations due to more detailed information related to TTF conditions (including 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 parameters can influence the prediction of TTF, associated available internal energy in the system and 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 (i.e., thermal conductivity, heat capacity)
- Minimum required cooling load and duration if using sprinkler systems

References

[1] Amorós, M., Dunjó, J., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Quantitative Risk Assessment. Foundation of Process Safety and Loss Prevention". An ioMosaic White Paper, ioMosaic Corporation.

[2] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Hazard Identification. Guidance for Identifying Loss of Containment Scenarios". An ioMosaic White Paper, ioMosaic Corporation.

[3] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Frequency Analysis. Estimating Frequencies of Occurrence and Conditional Probabilities of Loss of Containment". An ioMosaic White Paper, ioMosaic Corporation.

[4] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach – Damage Criteria. An Overview of State-of-the-Art Damage Criteria for People and Structures". An ioMosaic White Paper, ioMosaic Corporation.

[5] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Consequence Analysis. An Introduction to Consequence Modeling and Identification of Outcomes from Loss of Containment Scenarios". An ioMosaic White Paper, ioMosaic Corporation.

[6] Amorós, M., Dunjó, J., Prophet, N., Gorski, G., 2016. "Risk-Based Approach – Risk Evaluation. Tools for Risk Characterization". An ioMosaic White Paper, ioMosaic Corporation.

[7] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach – Fires. Introduction to Fires and Dynamic Thermal Stress Analysis". An ioMosaic White Paper, ioMosaic Corporation.

[8] Reniers, G., Cozzani, V., 2013. "Domino Effects in the Process Industries, Modeling, Prevention and Managing". Elsevier, Amsterdam.

[9] Amorós, M., Dunjó, J., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Risk Evaluation. Tools for Risk Characterization". An ioMosaic White Paper, ioMosaic Corporation.

[10] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Domino Effect and Escalation Triggered by Fires. Combining Exceedance Curves and Time to Failure Simplified Methodologies". An ioMosaic White Paper, ioMosaic Corporation.

[11] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach -Domino Effect and Escalation Triggered by Explosions. Combining Exceedance Curves and Overpressure Threshold Criteria". An ioMosaic White Paper, ioMosaic Corporation.

[12] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Domino Effect and Escalation Triggered by Explosions. Combining Exceedance Curves, Single Degree of Freedom and Pressure-Impulse Diagrams". An ioMosaic White Paper, ioMosaic Corporation.

[13] API Standard 521, 2014. "Pressure Relieving and Depressuring Systems". Sixth Edition. American Petroleum Institute (API).

[14] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Fires. Introduction to Fires and Dynamic Thermal Stress Analysis". An ioMosaic White Paper, ioMosaic Corporation.

[15] ioMosaic Corporation, SuperChems™ a component of Process Safety Office™, ioMosaic; http://www.iomosaic.com/software/process-safety-office-.

[16] API Standard 526, 2002. "Flanged Steel Pressure Relief Valves". Fifth Edition. American Petroleum Association (API).