Catastrophic Vessel Failure due to Fire Exposure: Wall Dynamics & Consequence Analysis

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Abstract

Vessel rupture is typically caused by an increase in the internal energy of the vessel contents and insufficient emergency relief. Under fire exposure or internal heating by a runaway reaction, or both, the vessel wall temperature increases, the tensile strength of the vessel walls metal decreases, and resistance to internal pressure decreases. Vessel wall dynamics analysis is a valuable tool capable of predicting not only when the vessel is expected to fail (i.e., stress due to internal pressure is greater than the ultimate tensile strength) but also at what temperature, pressure, and fluid composition. These conditions form the basis for consequence analysis. The available internal energy in the system is a source of fragmentation and deformation energy for the vessel shell, kinetic energy imparted to contents and fragments, and blast wave energy.

The present paper illustrates two selected systems under pool fire exposure. A detailed analysis is provided for the parameters that influence the predicted Time to Failure (TTF) and the internal available energy in the system when failure is predicted. Two key parameters that influence the expected level of vessel failure risk under fire exposure (i.e., TTF) include scenario frequency of occurrence and the available internal energy of the vessel contents.

1. Introduction

Loss of containment scenarios caused by catastrophic vessel failure can lead to severe consequences including fire, explosion, blast wave damage, and/or a toxic cloud moving across the property and into the surroundings **[1].** This particular type of scenario may lead to severe consequences, as evidenced by the analysis of past incidents, which confirmed that more than half of the industrial "domino" incidents that occurred between 1961 and 2010 involved fire exposure as a primary event. Secondary targets affected were mostly pressurized tanks, atmospheric tanks, process vessels and pipelines **[2]**.

The proper quantification and understanding of scenario frequencies, actual vessel and piping failure potential, and any associated consequences can provide for better risk management and allocation of resources for risk reduction. Since fire is the primary event, an accurate model to predict the heat load due to fire is required. The last revision of API-521 **[3]** includes a fundamental equation for estimating the heating rate into the vessel walls:

$$\boldsymbol{q_w = \alpha_w \varepsilon_f \sigma T_f^4 + h\left(T_{f,g} - T_{w,t}\right) - \varepsilon_w \sigma T_{w,t}^4} \qquad \text{[Equation 1]}$$

The explanation of Equation 1 follows the same rationale illustrated by Melhem & Gaydos **[1]**. 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. Finally, the third term is the heat flux that is re-radiated by the external wall or insulation surface.

When SI units are used, q_w is the net heat flux reaching the wall or insulation surface in W/m^2/K, α_w is the external wall surface or insulation absorptivity, ε_f is the flame surface emissivity, σ is the Stefan–Boltzman constant (i.e., 5.67E-08 W/m^2/K^4), T_f is the flame surface temperature in K, h is the combustion gases convective heat transfer coefficient in W/m^2/K, $T_{f,g}$ is the combustion gases temperature in K, $T_{w,t}$ is the time dependent wall surface temperature, and ε_w is the external wall or insulation surface emissivity. Recommended values are provided by API-521 **[3]** and Melhem **[1].**

Equation 1 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. The Ultimate Tensile Strength (UTS) of the material of construction decreases. 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 in the region wetted by the liquid remains near the liquid temperature because of the high rate of heat transfer between the liquid and the vessel wall. Accordingly, 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.

The fire heat load is one of the key parameters that influence the duration between when the fire starts and the eventual equipment failure leading to a loss of containment scenario. 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). Thus, this time lapse (i.e., TTF) is an important parameter to be characterized for the protection and prevention of escalation triggered by fire exposure (i.e., the domino effect) **[2]**.

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.

The present paper analyzes two selected systems under a pool fire exposure and illustrates how the wall segmentation approach can be valuable for predicting the TTF and associated conditions: (1) how likely is a catastrophic failure due to fire exposure (i.e., frequency of occurrence) and (2) how severe are the associated impacts.

2. Study Approach

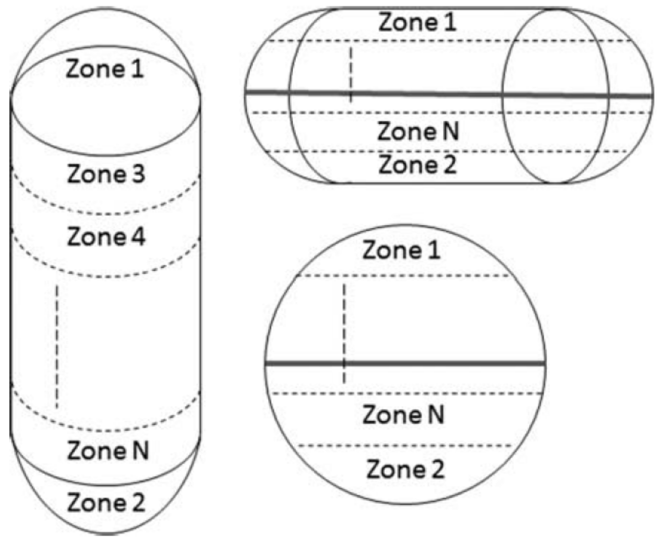
2.1 Wall Dynamics

Estimating the TTF requires 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 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, sub-cooled liquid flow, and multiphase flow with/without slip **[4]**.

The two selected case studies evaluated in the present paper used SuperChems Expert^{TM}, a component of ioMosaic's Process Safety Office^{TM} **[5]**. The vessel dynamics models in SuperChems Expert^{TM} 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 1. Detailed heat transfer to/from the surroundings and between the zones is dynamically accounted for. The ability to divide an equipment into multiple segments allows to closely examine the dynamics of the fluids 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: (1) ambient to wall segment heat transfer options include insulation, solar heating, rain, water sprays, pool fires and flame jets (i.e., radiation and convection); (2) 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 are modeled as constant values during the simulation and also over the vessel height.

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.

Figure 1. SuperChems Expert^{TM} Segmentation Scheme



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 **[6]**.

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 allows determination of the vent volumetric discharge rate.

The vessel flow models implemented in SuperChems Expert^{TM} 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 and specific hydrodynamic models implemented in SuperChems Expert^{TM}, 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 metal segments UTS as a function of time and temperature. Simulations typically consider 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 **[1].**

2.2 Consequence Analysis

The TTF prediction not only provides the lapsed time from the fire start (i.e., valuable information for the decision-making process) but also defines the associated temperature, pressure and fluid composition 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. The rate of pressure drop influences this pressure undershoot which in turn influences the superheat available for bubble nucleation. Large depressurization rates can lead to large undershoots and thus 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.

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 (see **[4]**, **[5])**. 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).

3. Case Studies and Results Illustration

3.1 Case Studies Description

Table 1 illustrates the key parameters that define the two (2) selected systems analyzed in the present paper. Both systems are assumed to be under fire exposure.

Table 1. Systems Analyzed

Parameter	Units	System I	System II
Maximum Allowable Working Pressure, MAWP	[psig]	325.0	204.0
Design or limiting temperature	[ºF]	650.0	650.0
Actual material of construction	[-]	SA-516-G70	SA-516-G70
Length (straight side for cylinders)	[ft]	31.40	35.20
Inside diameter	[ft]	3.325	3.528
Shell wall thickness	[ft]	0.0521	0.0421
Left Head	[-]	Flat/None	Flat/None

Parameter	Units	System I	System II
Right Head	[-]	Elliptical 2:1	Elliptical 2:1
Mass of internals	[lb]	55,522	66,050
Total Surface Area	[in^2]	50,208	59,531
Total Volume	[ft^3]	277.5	349.9
Bottom elevation above location where liquids can pool	[ft]	0.000	0.000
Mixture composition	[-]	Liquid Crude	HVGO
Relief pressure > Critical pressure?	[-]	No	Yes
Initial liquid level	[%]	100	100
Fire properties: Flame temperature / Gas temperature	[ºF]	1,922	1,922
Fire properties: Emissivity / Absorptivity	[-]	0.75	0.75
PSV size based on API	[-]	6Q8	1F2

Three (3) simulation cases have been considered for each system:

1. Case 1: no credit for any relief system and no credit for fire-proof insulation
2. Case 2: credit for an adequate pressure relief valve, and no credit for fire-proof insulation
3. Case 3: credit for an adequate pressure relief valve, and credit for fire-proof insulation

For all cases analyzed, the vessel walls were divided into five segments and dynamic simulations have been performed via SuperChems Expert^{TM}. Additionally, the fire heat flux for all cases is determined using Equation 1.

3.2 Case Studies Analysis

3.2.1 Case 1: Analysis of Systems I and II

A liquid-full vessel exposed to fire without any installed relief path will rapidly overpressure due to the small magnitude of the isothermal compressibility factor of the liquid (i.e., significant increase in pressure for small increases in temperature). Taking into account the thermal inertia due to the vessel metal, the estimated TTF in both systems is expected to be lower than 5 minutes (e.g., 3.97 and 2.57 minutes for system I and system II, respectively). Thus, isolated full-liquid vessels under fire exposure are expected to fail due to overpressure rather than over-temperature. The TTF predicted in this case assumed no credit for leaks through gaskets, flanges, etc.

3.2.2 Case 2: Analysis of Systems I and II

Figure 2 (system I) and Figure 3 (system II) illustrate the predicted pressure history and highlight the pressure relief valve (PRV) cycling process during two (2) hours of simulation time.

Figure 4 (system I) and Figure 5 (system II) illustrate the predicted wall temperature profile for all five vessel metal segments. The walls in contact with the vapor space become hotter than the walls in direct contact with the liquid contents. The liquid level is ultimately depleted (vaporized), and thereafter the metal segments that become dry are heated more quickly. It is important to consider the impact of the onset of two-phase flow from a PRV and/or a depressuring valve when they are actuated. The heat stored in the vapor walls can ultimately be recovered by the vessel contents during two-phase swell and/or flow since the vapor walls will get coated with a two-phase mixture.

Figure 6 (system I) and Figure 7 (system II) illustrate 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. System I is expected to fail after 67 minutes from the fire start, and system II only after approximately 20 minutes. This can be explained by analyzing the required time for evaporating all liquid contents. The liquid phase in system I is expected to be fully vaporized after 1 hour and 43 minutes from the fire start, while only 6 minutes are predicted for system II. This difference is due to the low ratio between the relief system pressure and mixture critical pressure in system II.

The PRV size also influences the TTF and associated conditions:

- The dynamic simulation illustrated in Figure 8 considers the same conditions as in system I, case II. However, 8T10 PSV has been selected. The main purpose of Figure 8 is to compare the results illustrated in Figure 6 (i.e., system I case II with a 6Q8 PSV). Figure 8 predicts a TFF of 85.5 minutes, i.e., 18 minutes later than TFF illustrated in Figure 6. This can be explained due to more cooling effects during relief through 8T10 PSV rather than through 6Q8PSV. Additionally, it is important to evaluate the mass remaining in the system when TFF is predicted: 519.4 lb and 377.6 lb for systems represented in Figures 6 and 8, respectively. The 8T10 PSV favors the minimization of the expected impacts due to a vessel catastrophic failure exposed to fire (i.e., larger TTF and less mass remaining in the system with equivalent pressure and temperature). However, this is a sensitivity analysis to be performed in a case-by-case basis. For example, an oversized PRV could cause the vessel to fail sooner at the re-seat point of the relief device because the liquid level is being lost faster and low heat transfer coefficient between equipment walls and vapor space.
- An undersized PRV will cause the vessel to fail due to overpressure from rapid thermal expansion.

Therefore, a PRV will not prevent catastrophic vessel failure due to fire exposure, but an optimized PRV ensures the best compromise by maximizing the TTF and minimizing the available internal energy. The simulation results illustrate that additional mitigation measures are required to prevent vessel failure (e.g., installing depressuring systems, insulation, water sprays).

Figure 2. Pressure History- System I; Case II; 6Q8 PSV

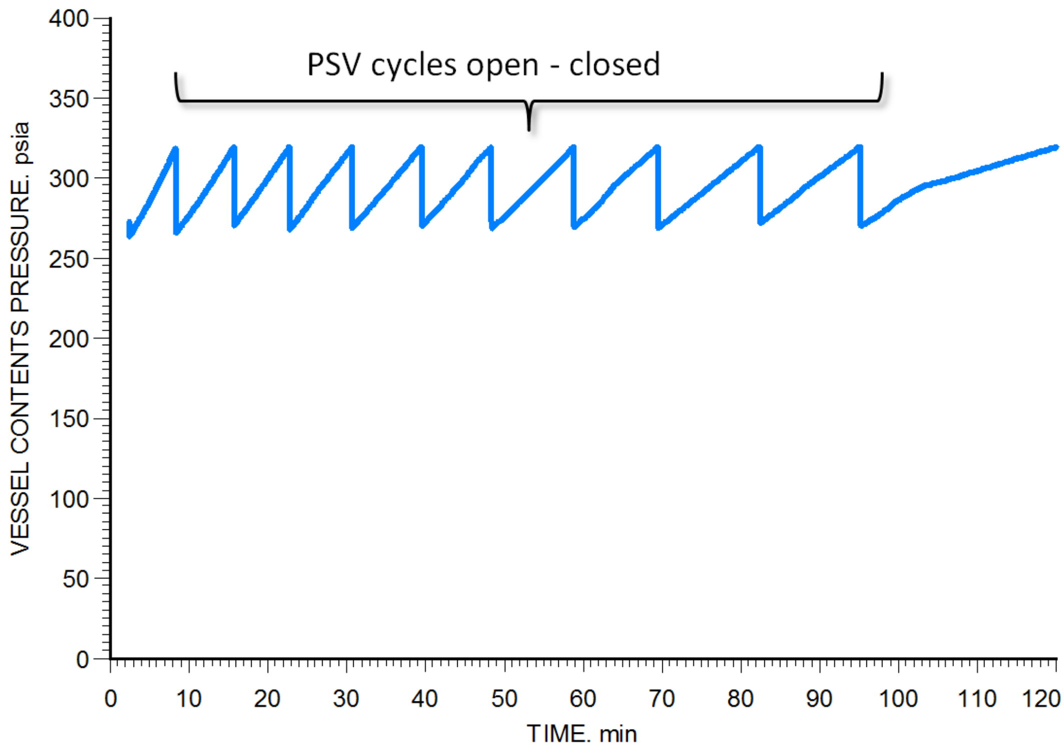


Figure 3. Pressure History- System II; Case II; 1F2 PSV

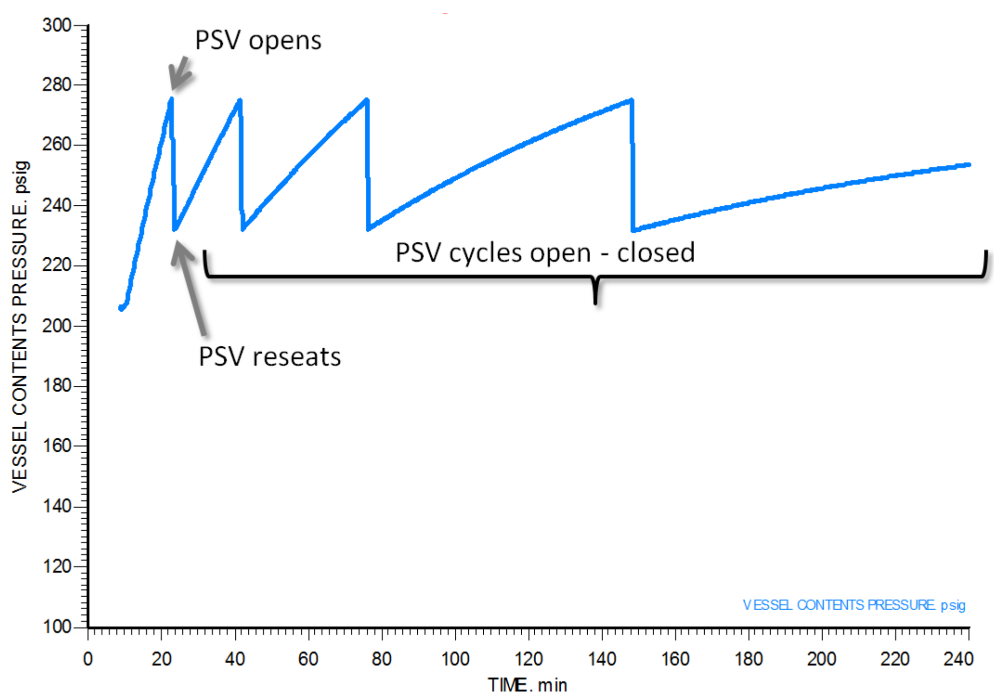


Figure 4. Wall Segments Temperature Profile- System I; Case II; 6Q8 PSV

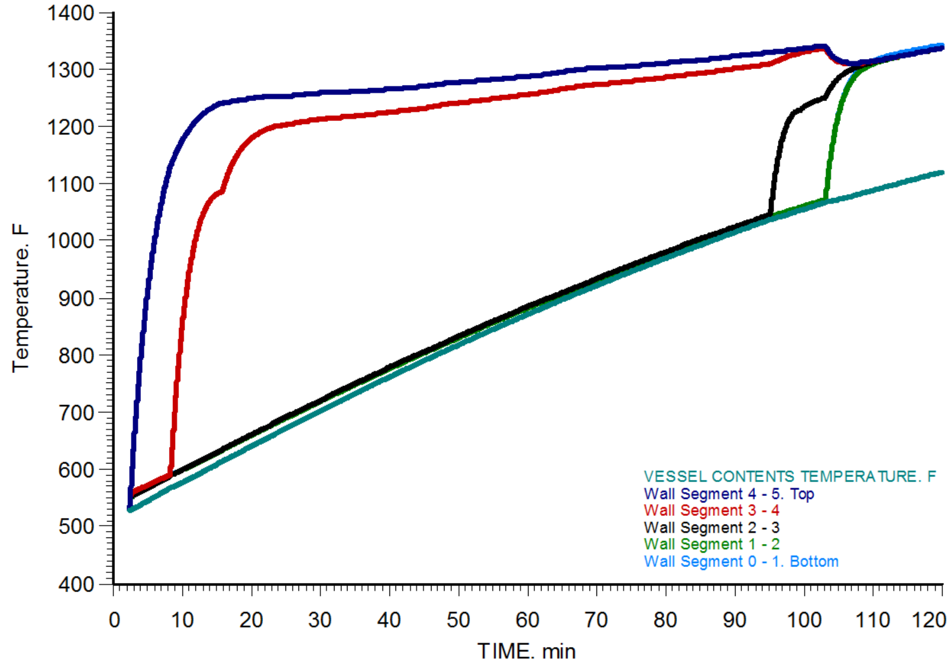


Figure 5. Wall Segments Temperature Profile- System II; Case II; 1F2 PSV

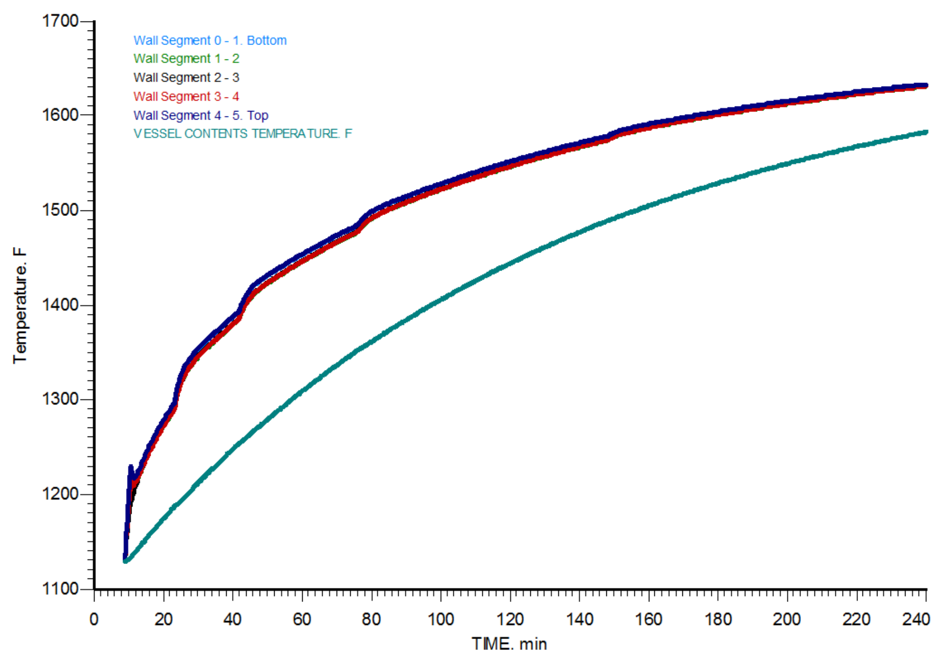


Figure 6. Wall Segments Stress Profile- System I; Case II; 6Q8 PSV

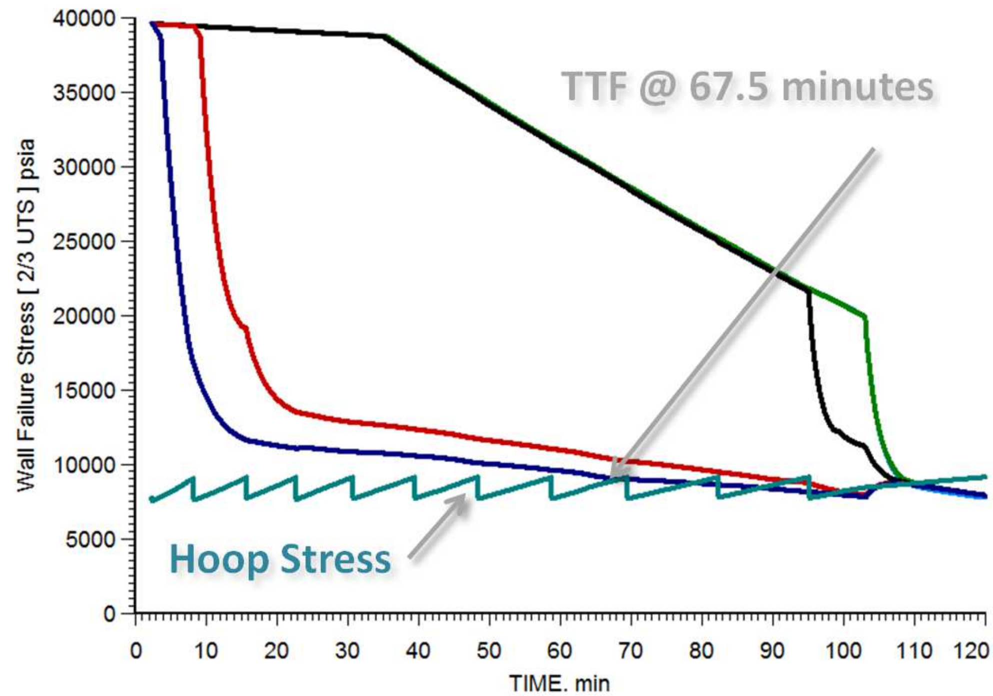


Figure 7. Wall Segments Stress Profile- System II; Case II; 1F2 PSV

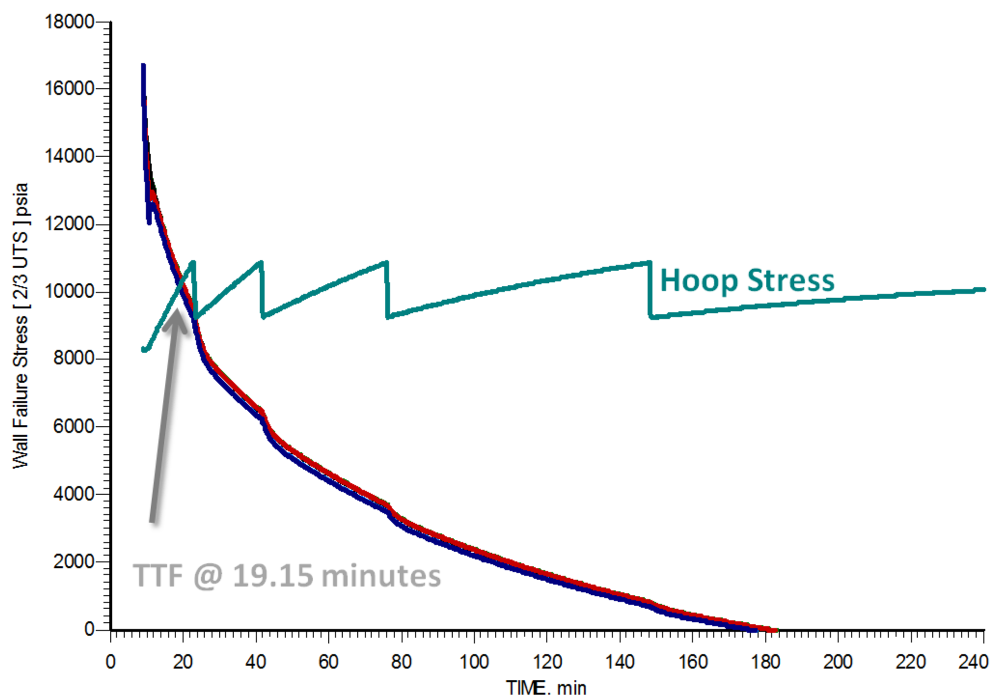
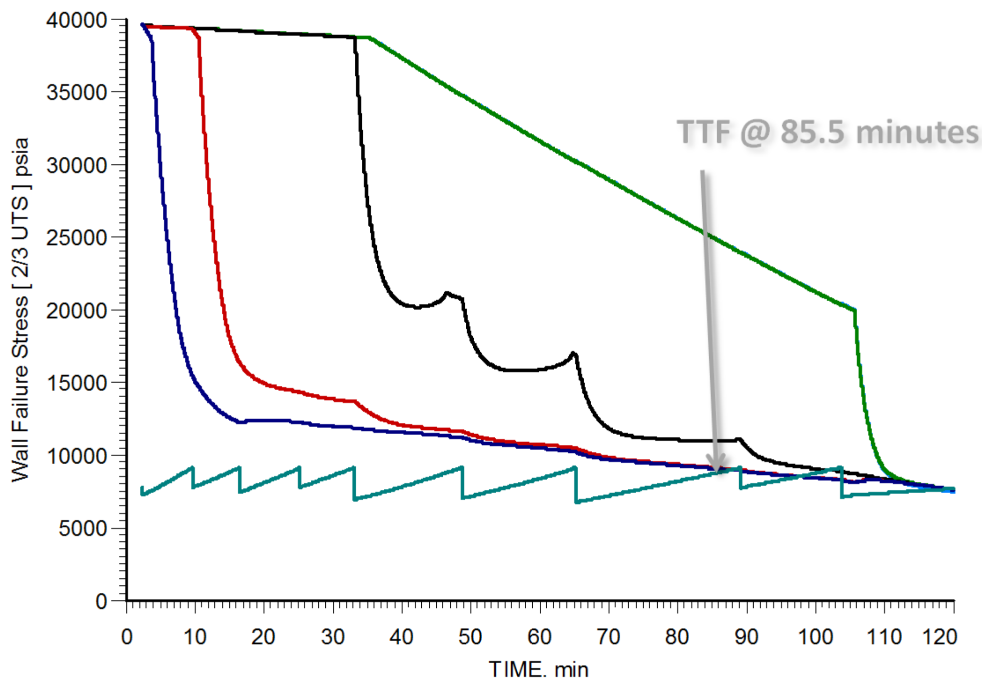


Figure 8. Wall Segments Stress Profile- System I; Case II; 8T10 PSV



3.2.3 Case 3: Analysis of Systems I and II

Case 3 is intended to illustrate how additional mitigation measures may impact on the TTF. This simulation specifically addresses both systems I and system II considered in case 2 but including one (1) inch of fire-proof insulation. The heat capacity and thermal conductivity data is considered as a function of temperature and used to refine the reduced heat transfer between fire and vessel walls. Figure 9 (system I) and Figure 10 (system II) illustrate the wall segments temperature profile and Figure 11 (system I) and Figure 12 (system II) illustrate wall stress history. Results for both systems confirm that the vessels are not expected to fail. Thus, the combination of an adequate PRV, and the installation of 1 inch of fire-proof insulation ensure the mechanical integrity of the system during 2 hours of a pool fire exposure.

Figure 9. Wall Segments Temperature Profile- System I; Case III

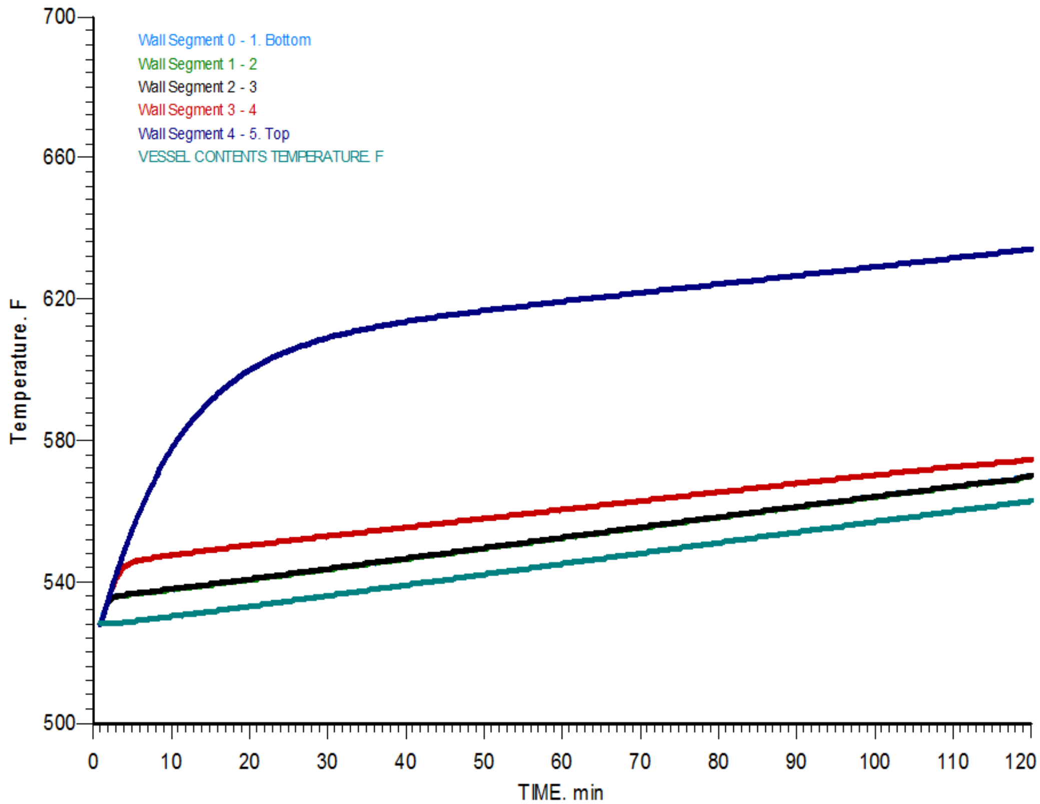


Figure 10. Wall Segments Temperature Profile- System II; Case III

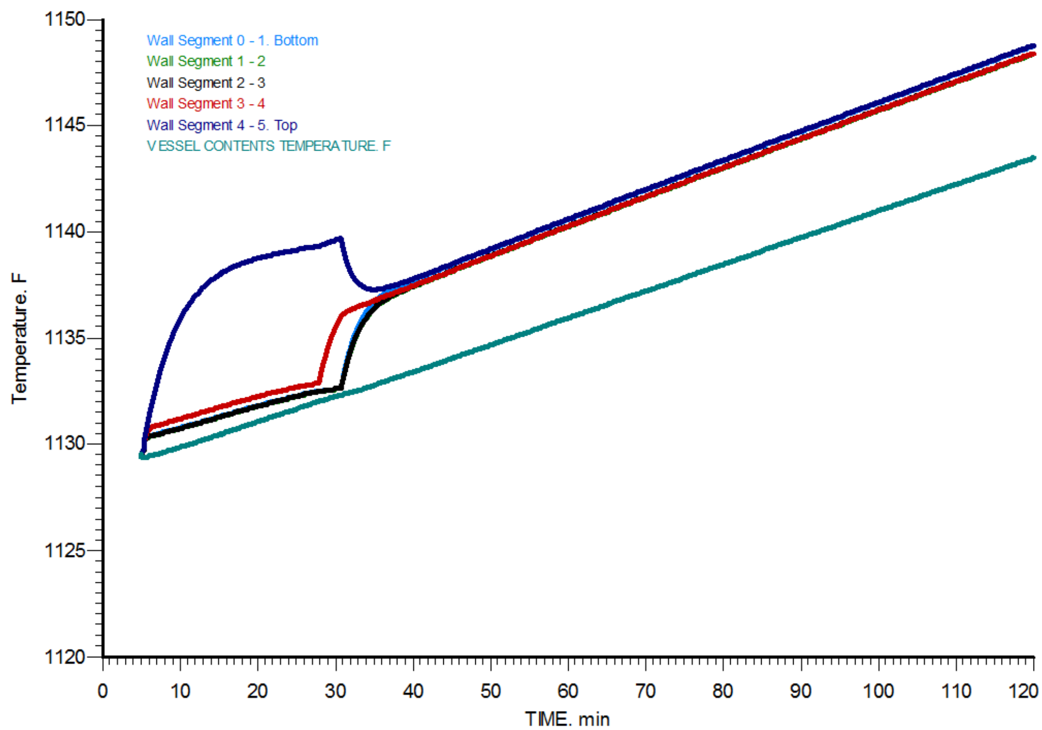


Figure 11. Wall Segments Stress Profile- System I; Case III

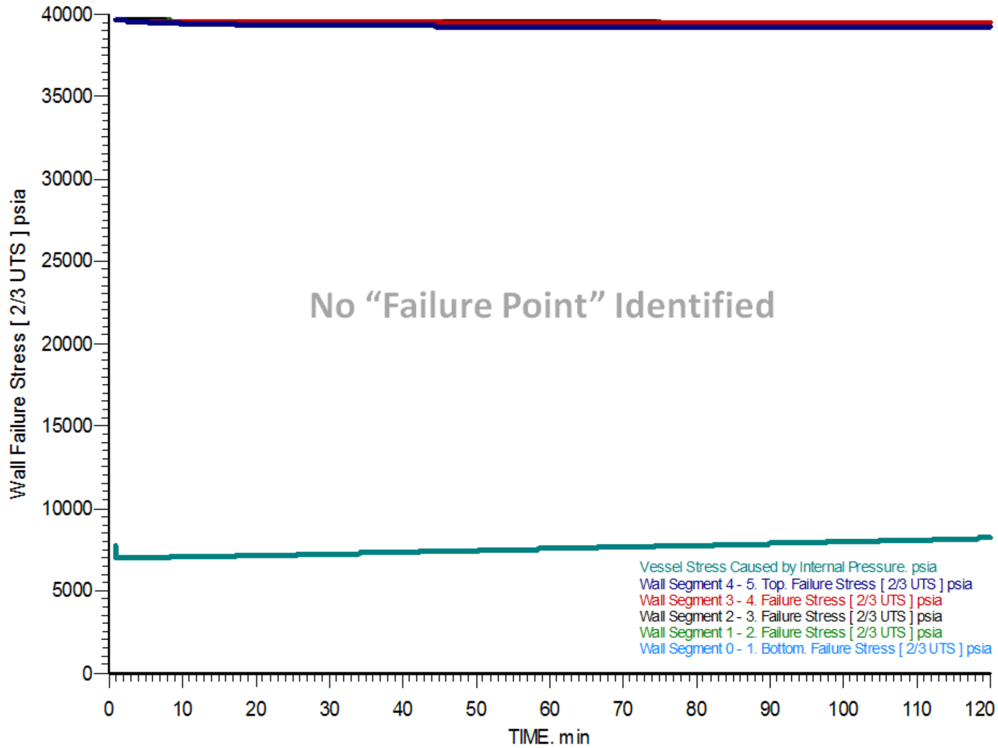
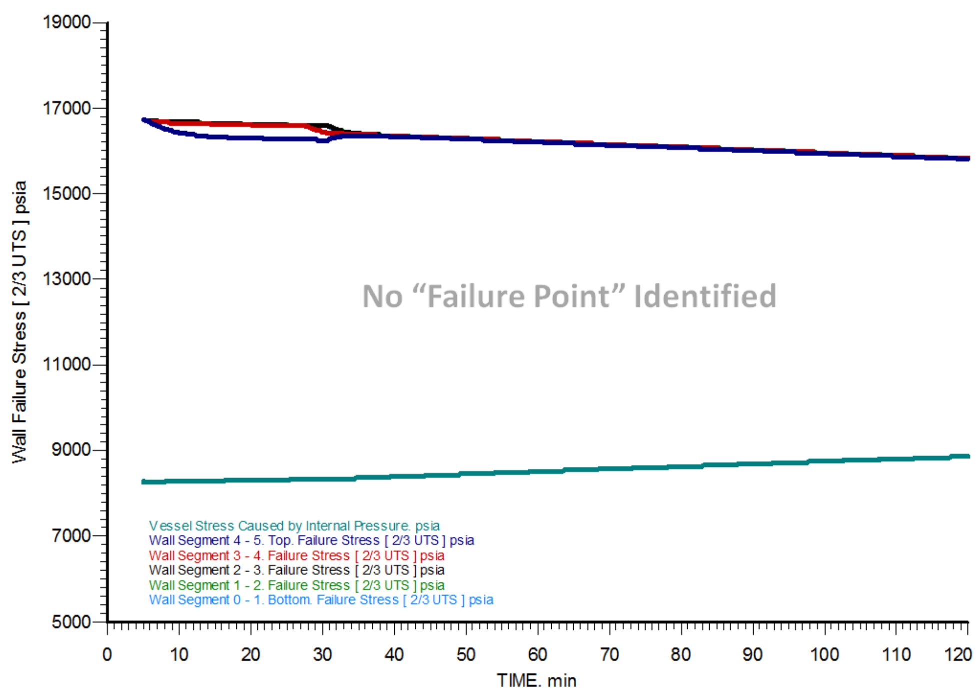


Figure 12. Wall Segments Stress Profile- System II; Case III



4 Conclusion

The mechanical integrity of two systems under fire exposure has been analyzed using the vessel wall segmentation approach implemented in SuperChems Expert^{TM}. The simulations confirm the following conclusions:

- A pressure relief valve does not ensure the mechanical integrity of a system under fire exposure, and additional mitigation measures are required to be considered.
- The size of the selected PSV influences the predicted vessel Time to Failure (TTF) and conditions remaining in the system. An optimum PSV size can be predicted via sensitivity analysis with the aim to maximize the TTF.
- Effective additional mitigation measures include installation of depressuring valves, fire-proof insulation, and 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 accurate consequences and risk estimations due to more detailed information related to TFF conditions (i.e., mass remaining in the system, mixture composition, pressure and temperature).

The vessel wall segmentation approach is valuable for sensitivity analysis when considering the following key four (4) parameters that could be installed in the system and which directly influence the TTF prediction:

- 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

5. References

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