

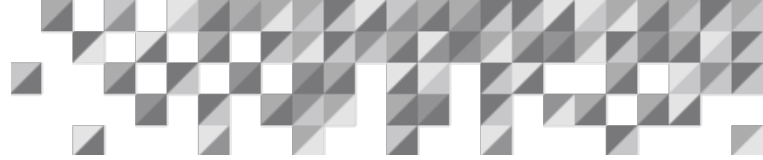


# **Mechanical Integrity Considerations in LNG Depressuization A Sensitivity Analysis**

An ioMosaic White Paper

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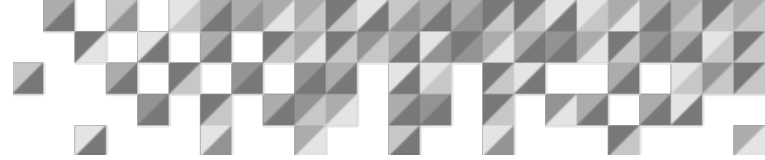


## **Abstract**

In a typical LNG installation, a rapid depressurization can cause cryogenic temperatures in both upstream and downstream connected process equipment and piping. This phenomenon, sometimes referred to as auto-refrigeration, can compromise the equipment's mechanical integrity and pose a risk of material embrittlement. As vessel metal walls are exposed to temperatures below the minimum design metal temperature (MDMT), permanent damage is possible. The potential for brittle failure is even more pronounced for a non-fire scenario. The level of severity depends on the initial pressure, initial temperature, content inventory, depressurizing rate, fluid composition, surrounding conditions, and heat transfer mechanisms.

Emergency depressurizing valves must therefore be sized to ensure a reasonable compromise between the impact of pressure and temperature. This paper examines the effects of different liquid levels, depressurizing valve sizes, vessel wall thicknesses, thermal insulations, and fluid compositions. The primary objective is to identify and illustrate the key factors that influence the mechanical integrity of a typical LNG installation, particularly at the mid to lower end of methane fluid compositions, and their impacts on carbon steel.

**Key words:** LNG, Depressurization Systems, Mechanical Integrity, Embrittlement, Vessel Wall Dynamics, Vessel Wall Segmentation Approach.



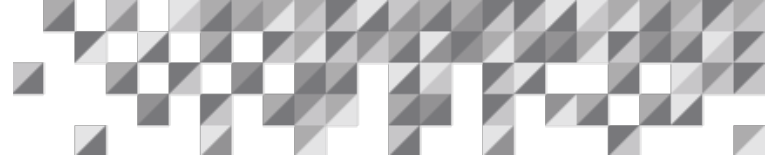
## Introduction

Emergency depressurizing systems (EDPs) are designed to reduce pressure by expelling the fluids and/or inventory from the protected equipment, thereby reducing the risk of equipment failure. Typical scenarios considered for emergency depressurization are external fire, uncontrolled reactions, and process vessel leaks.

In the event of a pool fire or jet flame impingement, not only do the system contents experience a rise in temperature and pressure, but the temperature of the system's walls rises as well. As the temperature of the metal increases, its mechanical strength decreases. Since the portion of the vessel filled with liquid predictably absorbs most of the heat, the main area of concern would be the unwetted or dry wall exposed to fire. As heating continues, the tensile strength is further reduced. Eventually, the wall metal temperature will reach the vessel's ultimate tensile strength, causing equipment failure.

Much literature<sup>1,3,4</sup> has been devoted to addressing system depressurization for fire scenarios; this paper focuses on the scenario of a vessel leak, alternatively referred to as a non-fired or cold depressurization. Due to expansion cooling and condensation of light ends, rapid depressurization can cause cryogenic temperatures in both upstream and downstream connected process equipment and piping. Depressurization systems in typical LNG installations often experience this phenomenon, known as auto-refrigeration, which may compromise the equipment's mechanical integrity and pose a risk of material embrittlement. As system walls are exposed to temperatures below the minimum design metal temperature (MDMT), permanent damage is possible. The potential for brittle failure is even more pronounced for a non-fire scenario. Its severity depends on the initial pressure, temperature, content inventory, depressurizing rate, fluid composition, surrounding conditions, and heat transfer mechanisms.

Emergency depressurizing valves (EDPV) must therefore be sized to ensure a reasonable compromise between the impact of pressure and temperature. For example, in the event of fire or abnormal heating, a larger EDPV size would generally lower pressure faster, likely meeting the established pressure reducing criteria (e.g., 100 psi or 50% of the initial pressure) in the specified amount of time (often at 15 minutes). However, a larger EDPV size would also generate a higher depressurizing rate, exacerbating the cryogenic effect, which ultimately leads to a lower metal temperature. Likewise, a larger liquid inventory may provide a better liquid contact for heat absorption and sustain the vessel integrity for longer in the event of abnormal heating. However, the larger liquid inventory may also expose the metal wall (at the bottom in contact with the cryogenic liquid) to the lower temperature longer, creating a higher probability of embrittlement failure.



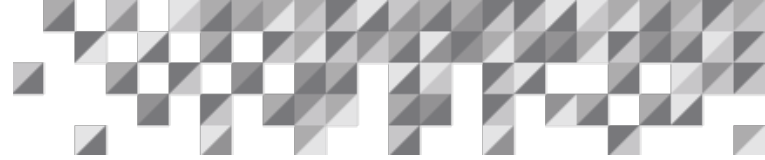
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## Basis for Sensitivity Analysis

The system chosen for this paper’s sensitivity analysis study entails a horizontal cylindrical vessel with 2:1 Elliptical heads with Carbon Steel SA-516-G70. Unless stated otherwise, the basis and mixture composition considered in all vessel wall dynamics analyses are summarized in Table 1 and Table 2.

**Table 1: System Specifications and Conditions**

Parameter	Value
Length [straight side for cylinders] [m]	6.0
Inside Vessel Diameter [m]	3.0
Shell and Head Thickness [m]	0.0127
Total Vessel Surface Area [m <sup>2</sup> ]	76.1
Total Vessel Volume [m <sup>3</sup> ]	49.5
Initial Vessel Wall Temperature [°C]	25
Ambient Temperature [°C]	25
Relative Humidity [%]	70
Wind Speed at reference height [m·s <sup>-1</sup> ]	2
Wind speed reference height [m]	10
Parameter	Value

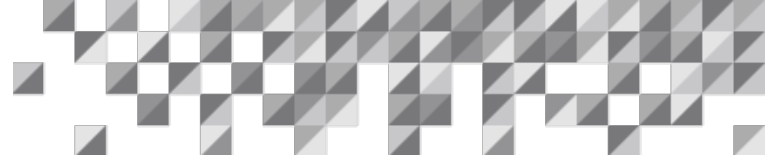
**Table 2: Mixture Composition**

Compound	Mole Fraction
METHANE	0.413
ETHANE	0.165
PROPANE	0.165
ISOBUTANE	0.257

Five (5) main cases were analyzed, examining the sensitivity of vessel wall thicknesses, initial liquid levels, EDPV sizes, insulation thicknesses, and fluid compositions. Table 3 provides a summary of the parameters considered in this study.

**Table 3: Summary of Sensitivity Analysis Cases**

Case	Description
Vessel Wall Thickness	Four (4) wall thicknesses (0.01", 1.5", 3.0", and 20"), considering 10% initial liquid level and an EDPV size of 4"
Initial Liquid Level	Three (3) initial liquid levels (10%, 50%, and 90%), considering all EDPV sizes
EDPV Size	Four (4) EDPV sizes (0.5", 1.0", 2.0", and 4.0"), considering all initial liquid levels
Insulation Thickness	Four (4) insulation thicknesses (0", 2", 7", and 14"), considering all initial liquid levels and an EDPV size of 4"
Fluid Compositions	Six (6) methane mole fractions (0.05, 0.10, 0.20, 0.30, 0.40, and 0.5) at 10% initial liquid level and 22.5 barg using an EDPV size of 2"



Note that evaluating the various initial liquid levels and EDPV sizes results in a total of twelve (12) dynamic simulation runs. Likewise, combining the insulation thicknesses at all initial liquid levels equates to another twelve (12) runs. Adding the four (4) runs from the vessel wall thickness case (at 10% initial level and an EDPV size of 4”) and six (6) methane fluid compositions (at 10% filled level and 22.5 barg using an 2” EDPV size), a total of thirty four (34) dynamic simulation runs were conducted in this study.

Except for the methane fluid composition cases, all simulations considered the same mixture composition and same initial fluid temperature. However, to retain saturated conditions at the desired temperature for each selected initial liquid level case, the initial pressure was modified accordingly, as shown in Table 4.

**Table 4: Initial Saturated Conditions**

Initial Liquid Level [%]	Initial Pressure [barg]	Initial Fluid Temperature [°C]
10	22.5	0.00
50	50.0	0.00
90	62.8	0.00

Table 5 summarizes the Foam Glass properties while Table 6 provides the methane compositions at their associated saturated temperatures used in this study.

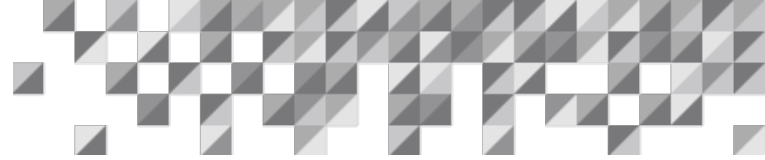


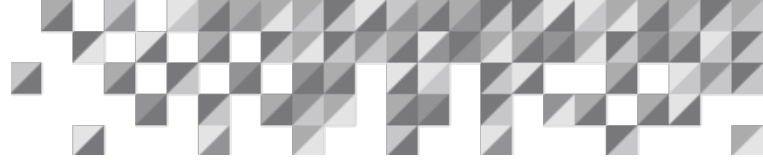
Table 5: Foam Glass Insulation Properties

Temperature [°C]	Density* [kg·m <sup>-3</sup> ]	Specific heat capacity* [kJ·kg <sup>-1</sup> ·K <sup>-1</sup> ]	Thermal Conductivity [W·m <sup>-1</sup> ·°C <sup>-1</sup> ]
-75	300	351.5	0.172
-50	300	351.5	0.180
-25	300	351.5	0.188
-10	300	351.5	0.197
0	300	351.5	0.201
10	300	351.5	0.205
25	300	351.5	0.209
50	300	351.5	0.222
75	300	351.5	0.234
100	300	351.5	0.247

\*Both insulation density and specific heat capacity are considered not temperature dependent

Table 6: Methane Compositions and Temperatures at 22.5 barg and 10% Filled Level

Item	Mole Fraction					
Methane	0.050	0.100	0.200	0.300	0.400	0.500
Ethane	0.165	0.165	0.165	0.165	0.165	0.165
Propane	0.165	0.165	0.165	0.165	0.165	0.165
Isobutane	0.620	0.570	0.470	0.370	0.270	0.170
Temperature (°C)	78.77	70.71	52.76	31.38	3.73	-26.12



Emergency depressurizing valves are often sized to ensure a reasonable compromise between the impact of pressure and temperature. A larger EDPV size (resulting in a higher depressurizing rate) generally reduces the system pressure in a shorter amount of time. However, this would also create a greater expansion cooling effect, resulting in a lower fluid temperature, which may compromise the mechanical integrity of the vessel.

Consistent with the depressurizing rate guidelines from API 521<sup>2</sup>, this analysis examines the following two key criteria:

- The studied system is depressurized to 6.89 barg (100 psig) or 50% of the initial pressure within 15 minutes of initiating depressurization
- Vessel wall metal temperature does not fall below the minimum design metal temperature. This criterion provides an assurance against brittle failure due to expansion cooling or auto refrigeration.

Based on the established criteria, the main variables of interest considered for this analysis are the temperature and pressure during the entire process of depressurization. Our focus is thus designed to answer the following questions:

- What is the lowest wall temperature (the bottom wall segment with direct contact of liquid) reached during depressurization?
- What is the pressure after 15 minutes of depressurization?
- At what time does the system pressure reach 50% of the initial pressure?
- When does the system pressure reach 6.89 barg (100 psig)?
- Whether and when the wall temperature reaches the minimum design metal temperature of carbon steel (-29 °C)?

## Study Approach

The sensitivity analysis study was performed using the SuperChems<sup>TM</sup> component of ioMosaic's Process Safety Office<sup>TM</sup>. The program consists of detailed models for simulating the fluid dynamics of vessels containing multi-phase fluids. 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. There is no limit on the number of zones a user can specify. The ability to subdivide a vessel into multiple segments allows users 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 jet flame impingement (which is out of the scope of this paper).



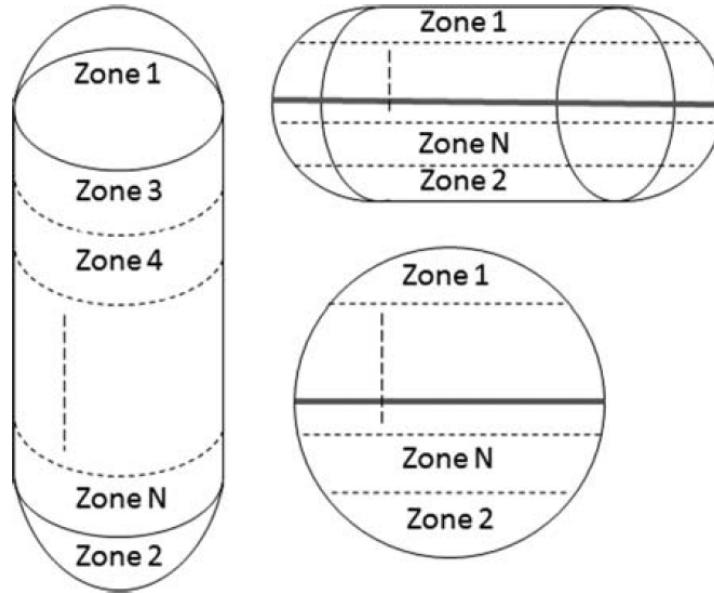
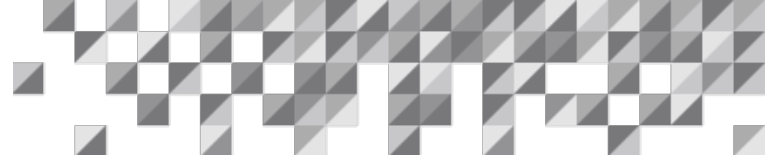


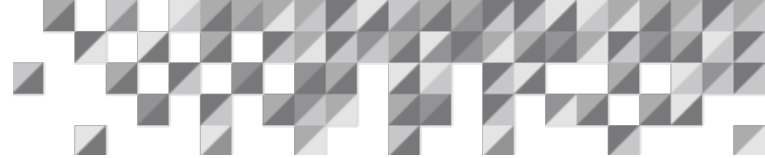
Figure 1: Vessel Segmentation Scheme

Figure 3 illustrates the added value of the vessel segmentation procedure via the vessel wall dynamics analysis. The illustrated simulation considers all parameters highlighted in Table 1 and Table 2 using a 50% initial liquid level and an EDPV size of 2 inches. The initial liquid height is estimated to be 1.5 meters. Based on the segmentation identified (with 10 wall segments as shown in Figure 2), the model confirms that segments 0 to 5 are in direct contact with the liquid. Wall segments 6 to 10 consist of the upper portion in contact with the vapor space of the vessel, where the metal walls are dry or unwetted.

Vessel Wall Heat Transfer Segment	Bottom Segment Elevation. m	Top Segment Elevation. m	Segment Metal Volume. m3	Segment Inner Surface Area. m2	Segment Outer Surface Area. m2	Wall-Fluid Conduction Length. m	Segment-Segment Bottom Contact Area. m2	Segment-Segment Top Contact Area. m2	Segment-Segment Conduction Length. m
Bottom Segment 0 -> 1	-0.013	0.121	0.108	8.372	8.927	0.013	0.000	0.460	0.472
Segment 1 -> 2	0.121	0.417	0.108	8.918	8.828	0.012	0.460	0.334	0.273
Segment 2 -> 3	0.417	0.757	0.108	7.529	7.531	0.014	0.334	0.301	0.341
Segment 3 -> 4	0.757	1.126	0.108	6.854	6.880	0.016	0.301	0.292	0.366
Segment 4 -> 5	1.126	1.500	0.108	6.357	6.390	0.017	0.292	0.289	0.374
Segment 5 -> 6	1.500	1.874	0.108	6.357	6.390	0.017	0.289	0.292	0.374
Segment 6 -> 7	1.874	2.243	0.108	6.854	6.880	0.016	0.292	0.301	0.366
Segment 7 -> 8	2.243	2.583	0.108	7.529	7.531	0.014	0.301	0.334	0.341
Segment 8 -> 9	2.583	2.879	0.108	8.918	8.828	0.012	0.334	0.460	0.273
Top Segment 9 -> 10	2.879	3.013	0.108	8.372	8.927	0.013	0.460	0.000	0.472

Figure 2: Detailed Vessel Segmentation

The minimum design metal temperature (MDMT) considered in this study is -29 °C, a typical criteria used for carbon steel material of construction. Figure 3 illustrates that the wall temperature



history of segments in direct contact with the liquid are expected to reach the MDMT in less than 20 minutes. However, the top segments (i.e., 6 to 10) are not expected to reach embrittlement temperatures due to the low wall/vapor heat transfer coefficient ( $5\text{-}100\text{ Wm}^{-2}\text{C}^{-1}$ ). This particular case has been selected to highlight the middle portion (Segment 5) of the vessel, which is in contact with both liquid and vapor vessel spaces. At approximately 400 seconds, Segment 5 is still in direct contact with the liquid. As the system is further depressurized, the liquid is reduced and Segment 5 transitions to more contact with the vapor space.

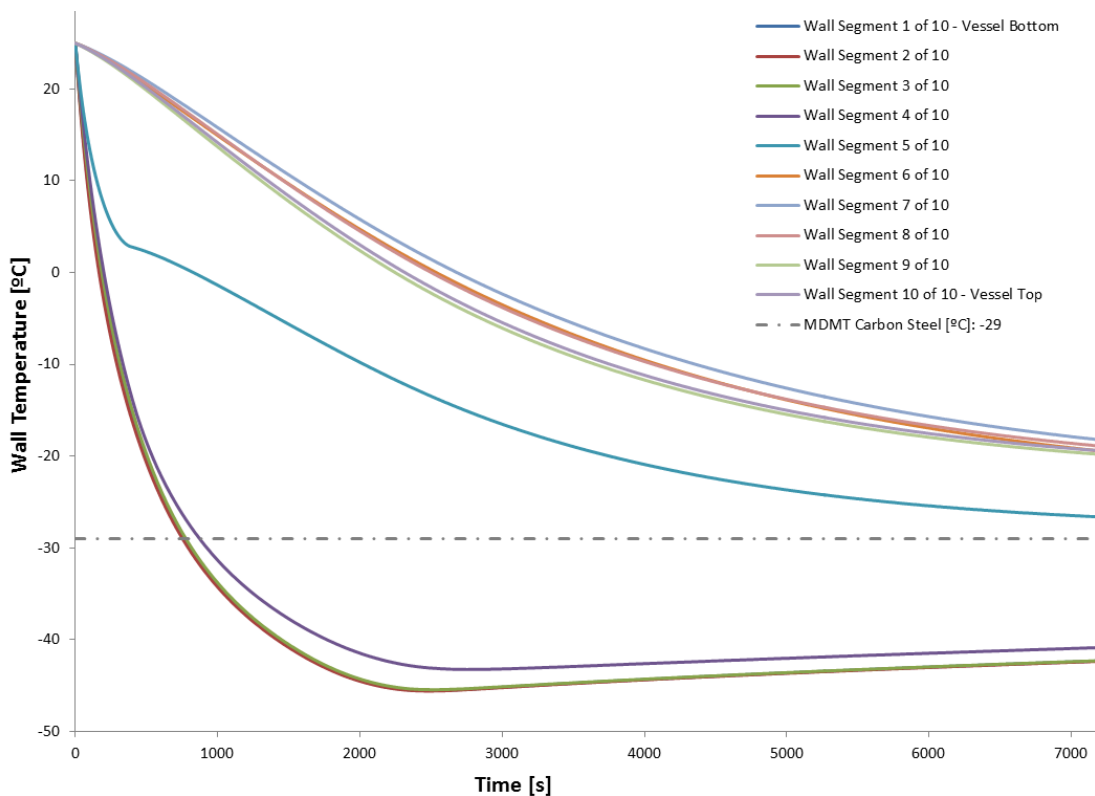
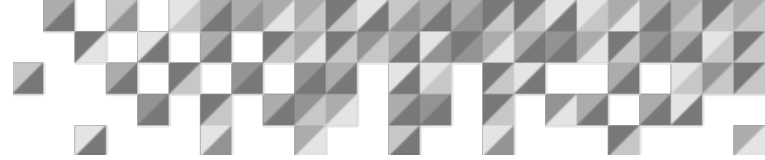


Figure 3: Wall Segment Temperature Profile (50% Initial Liquid Level, 2" EDPV)

Notice that as depressurization progresses, the rate of temperature decrease for Segment 5 slows, tilting the slope sideward and segregating from the other segments still in direct contact with liquid. This simple illustration highlights the significance and dynamic interface of liquid contact impact on the metal walls. It implies that the high value of wall/liquid heat transfer coefficient ( $100\text{-}10,000\text{ Wm}^{-2}\text{C}^{-1}$ ) accelerates the cryogenic fluid heat transfer to the metal wall, posing a higher risk of embrittlement failure.



## Analysis of the Results

The following sections illustrate how the selected parameters considered in this study influence the mechanical integrity of the vessel during the depressurization. Special attention has been focused on the bottommost wall segments of the vessel, which are expected to be in direct contact with the liquid during a cold depressurizing scenario.

### Impact of Vessel Thickness

This sensitivity analysis examines the impact of four (4) different vessel thicknesses (0.01", 1.50", 3.00", and 20.0"), evaluated using a 10% initial liquid level and an EDPV size of 4 inches. Figures 4 through 5 illustrate the results from the vessel wall dynamic analyses performed.

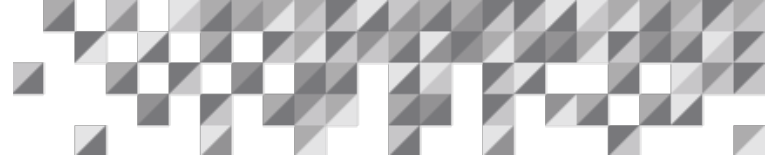
Table 7 illustrates the estimated metal mass according to the vessel thicknesses selected.

**Table 7: Vessel Shell and Heads Mass as a function of Vessel Thickness**

Thickness [inches]	Metal Mass [kg]
0.01	150.69
1.50	22,603
3.00	45,207
20.0	301,382

Source: SuperChems Expert™

Taking into account both the mass of the vessel shell and heads and the specific heat of the carbon steel, the wall temperature profiles during a depressurization process are shown. As illustrated in Figure 4, the lowest wall temperature predicted for the vessel thickness of 0.01 inches is -48.0 °C, which occurs approximately 5 minutes after depressurization begins. For vessel thicknesses of 1.5 inches or higher, the MDMT is not expected to be reached. Comparing Figure 4 (bottommost segment in direct contact with liquid) and Figure 5 (topmost segment in contact with the vessel vapor space) indicates that there is a higher risk of a vessel failure at the bottom of the vessel during a cold depressurization. On the contrary, the conclusion is the opposite for the case of a vessel under fire exposure. In the event of fire, the direct contact of fire



with the vapor space (top segments) is expected to rapidly increase the metal temperature. The metal strength may be reduced to a value lower than the internal vessel stress. As a result, the top section of the vessel is at a higher risk of failure.

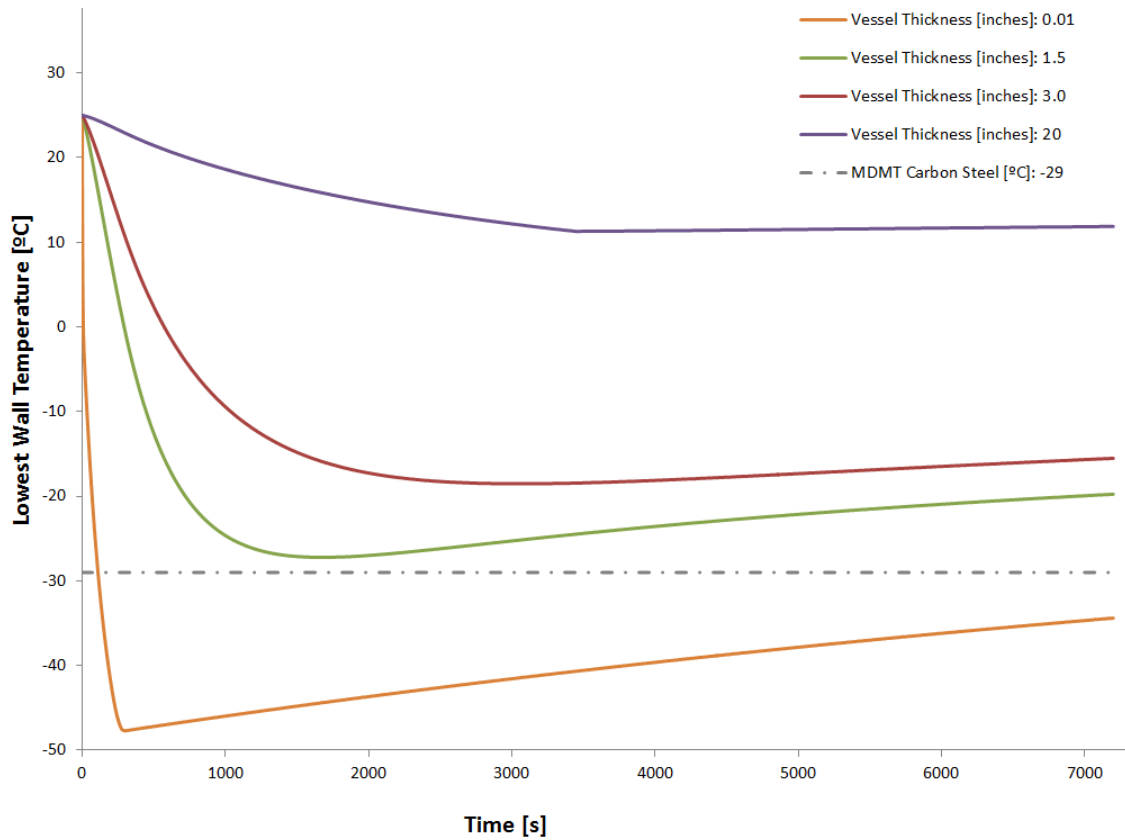


Figure 4: Lowest Wall Temperature History (Bottom Wall Segment; 10% liquid level; EDPV size 4")

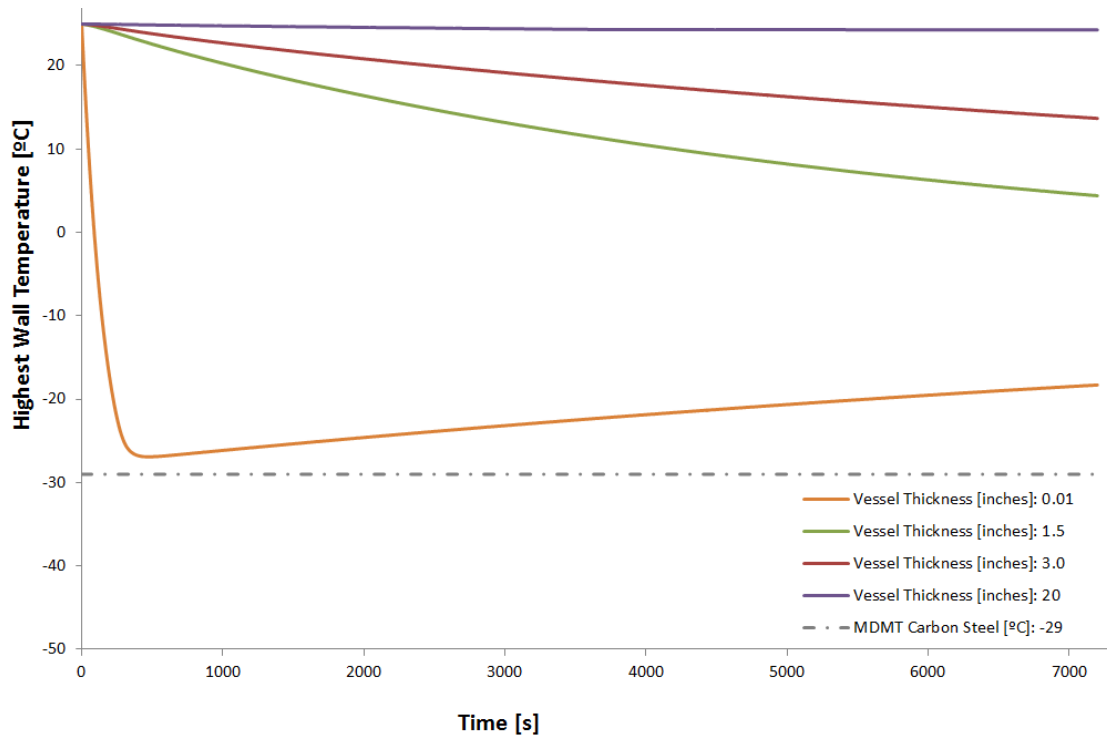
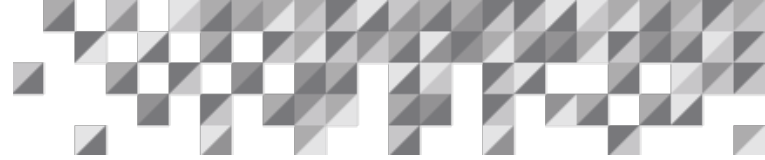


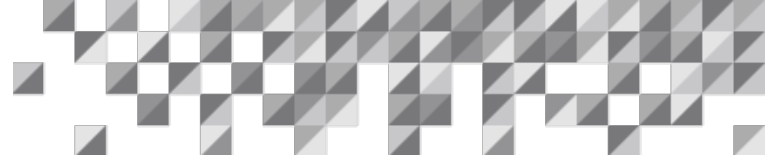
Figure 5: Highest Wall Temperature History (Top Wall Segment; 10% liquid level; EDPV size 4")

### Impact of Liquid Level and EDPV Size

This sensitivity analysis examines the impact of three (3) different initial liquid levels (10%, 50%, and 90%), evaluated at four (4) different EDPV sizes (0.5", 1.0", 2.0", and 4.0"). Together, there are a total of twelve (12) simulation runs.

Figures 6 through 11 illustrate both the pressure and wall temperature history results from the identified cases. Note that the temperature profiles are based on the bottommost segment of the vessel, assessing the metal wall in direct contact with liquid.

The lowest initial liquid level (10%) simulations with all EDPV sizes are shown in Figures 6 and 7. The diagrams indicate that the 0.5" EDPV size does not meet any pressure depleting criteria, although it maintains the temperature above the MDMT. In contrast, the pressure criteria are met for the EDPV sizes of 1", 2", and 4", but the metal temperatures fall below the MDMT, posing a risk of brittle failure.



The same situation is found for the remaining cases with 50% and 90% initial liquid levels, illustrated in Figures 8 through 11. Accordingly, the size of the EDPV influences how quickly the vapors are expelled from the system, and thus, how rapidly the system pressure is reduced. While a larger EDPV size depressurizes the system faster and meets the pressure reducing criteria, it also accelerates the cryogenic liquid heat transfer to the metal wall. According to the results, all cases highlight that an EDPV size of 4" will entail a wall temperature lower than the vessel MDMT. Note also that the rapid depressurization prolongs the contact time of the liquid portion of the fluid with the wall, confirming the impact of high heat transfer mechanisms in the liquid phase. This implies that higher liquid levels may pose a greater risk of material embrittlement. Conversely, a reduced initial liquid level results in a shorter contact time between the metal wall and the cryogenic liquid, providing a lower probability of brittle failure.

Figure 12 provides another perspective on the trend of using different EDPV sizes for a given system (using 10% filled level). It shows that larger EDPV sizes produce greater differences between the fluid and the metal wall temperatures. In other words, the vessel fluid temperature is predictably colder using a larger EDPV size, creating a larger driving force between the cryogenic fluid and the metal wall. Notice also that the temperature difference for all EDPV sizes ultimately converges at 2-3 °C after about 30 minutes, indicating steady state with minimal heat transfer driving force.

Note that these cases consider the default vessel thickness of 0.5 inch as outlined in the study basis. They are presented to demonstrate the needed compromise between the pressure reduction and wall temperature criteria. As a result of this analysis, a few actions could be recommended depending on the cycle lifetime of the system. If it is a new design, a greater vessel thickness should be explored. Changing the vessel's material of construction from carbon steel to stainless steel is also a viable alternative. For an existing system under operation, an optimized EDPV size may be required to achieve adequate depressurization while minimizing the auto-refrigeration effect. Alternatively, a combination of EDPV sizes with different activation times could be considered. Note also that an emergency depressurization system is often designed to handle both cold and fire depressurizations. An optimized scheme should therefore be established to address both situations.

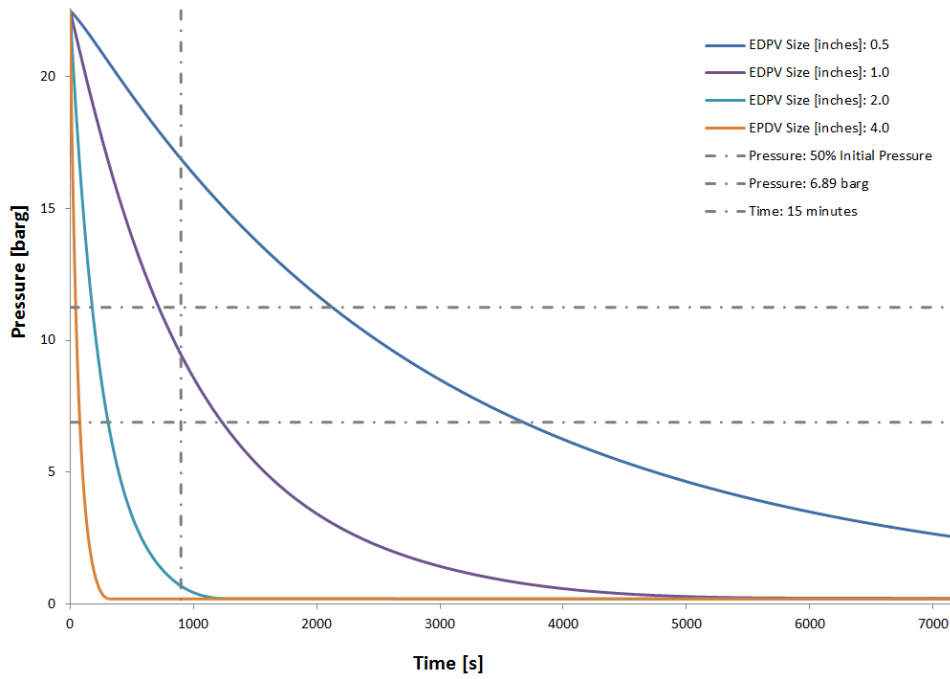
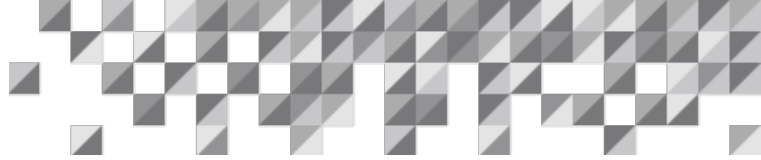


Figure 6: Pressure History (EDPV Size Sensitivity Analysis at 10% Liquid Level)

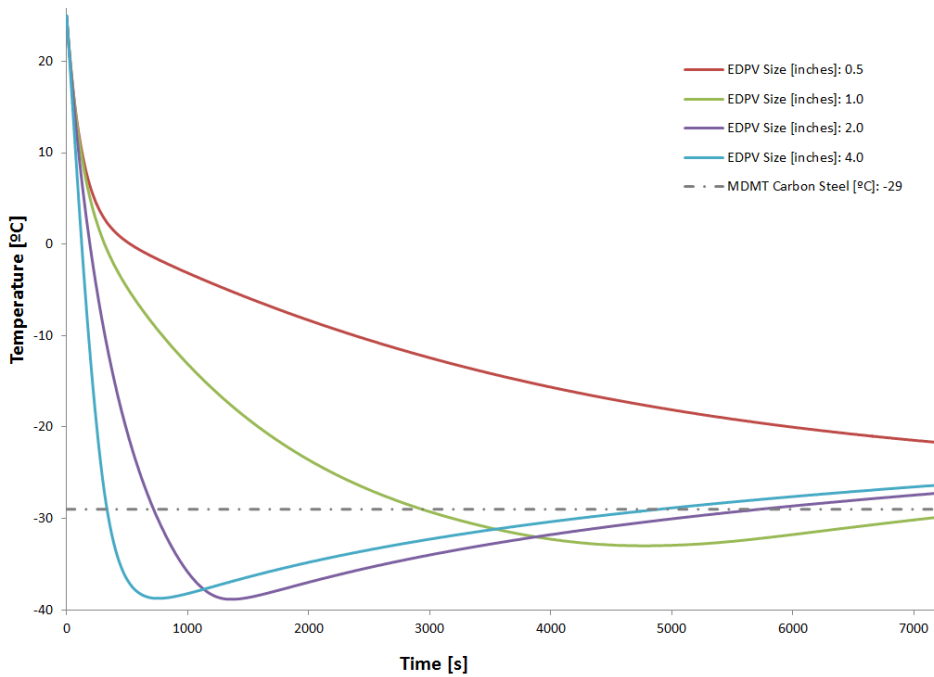


Figure 7: Wall Temperature History (EDPV Size Sensitivity Analysis at 10% Liquid Level)

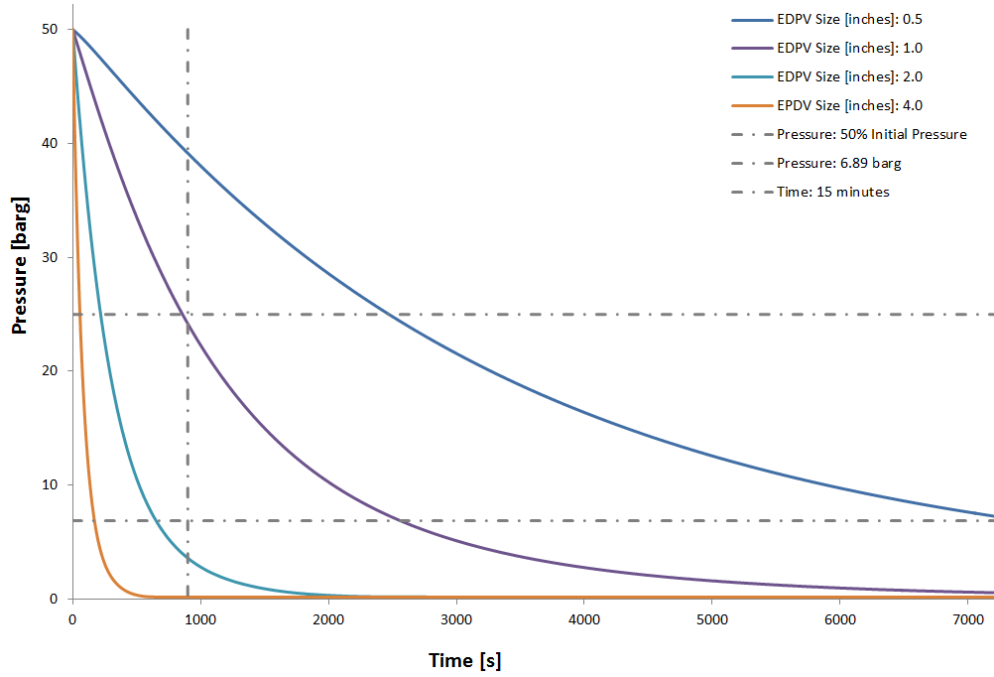
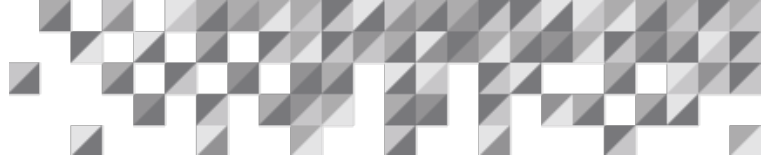


Figure 8: Pressure History (EDPV Size Sensitivity Analysis at 50% Liquid Level)

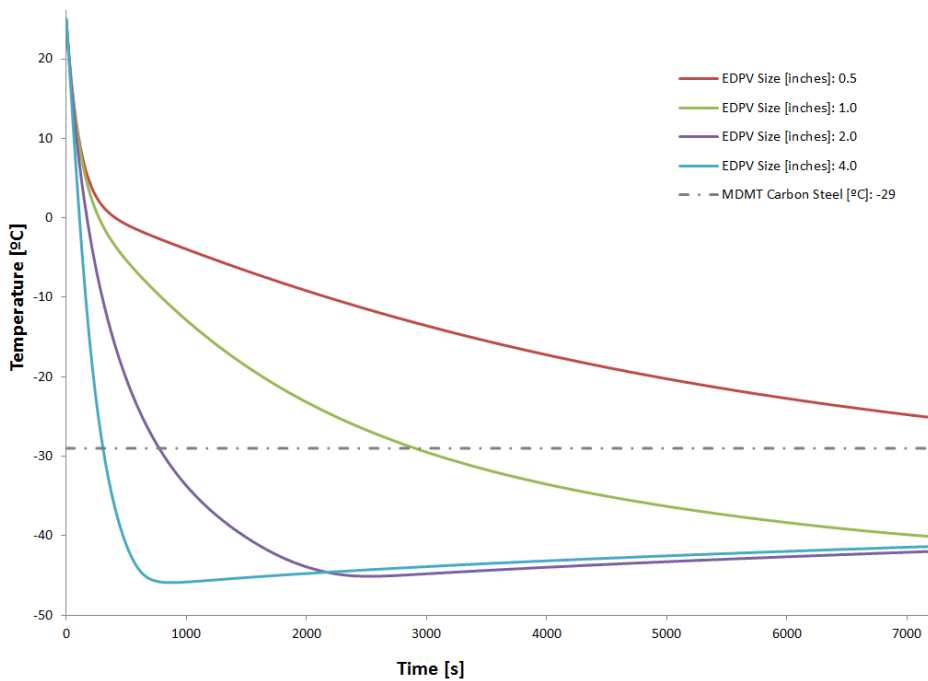


Figure 9: Wall Temperature History (EDPV Size Sensitivity Analysis at 50% Liquid Level)



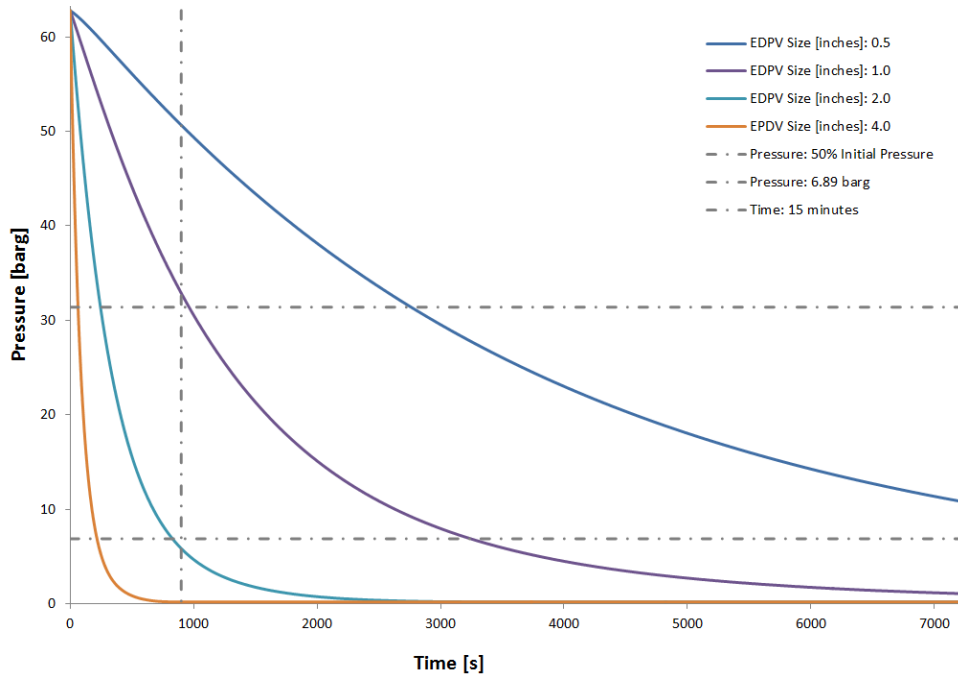
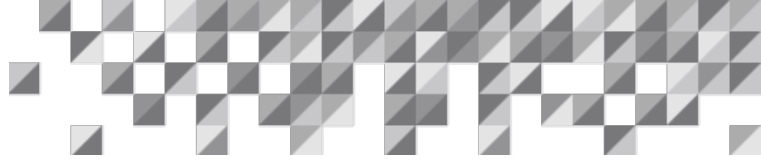


Figure 10: Pressure History (EDPV Size Sensitivity Analysis at 90% Liquid Level)

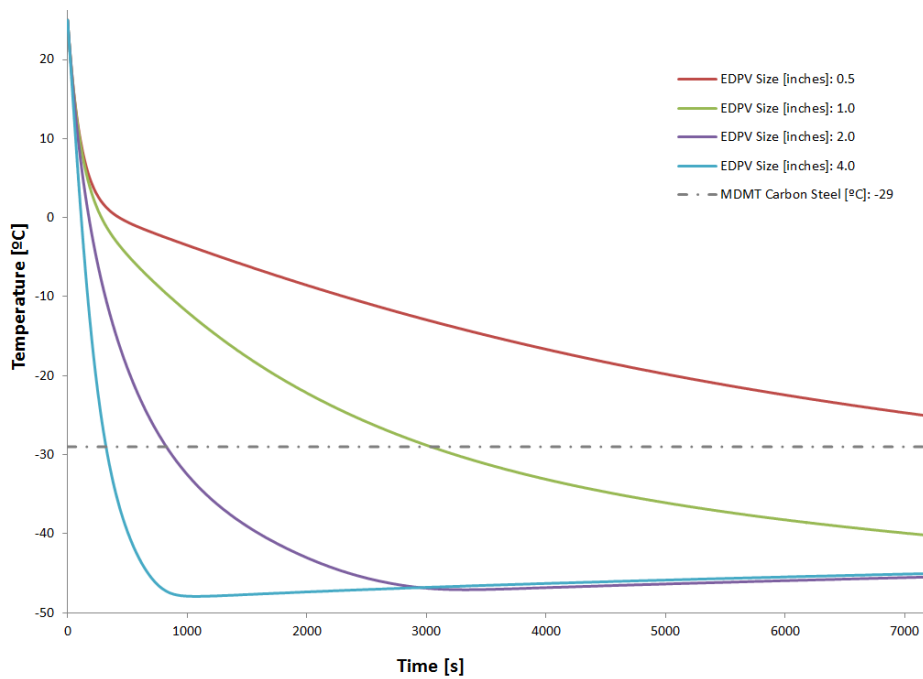


Figure 11: Wall Temperature History (EDPV Size Sensitivity Analysis at 90% Liquid Level)

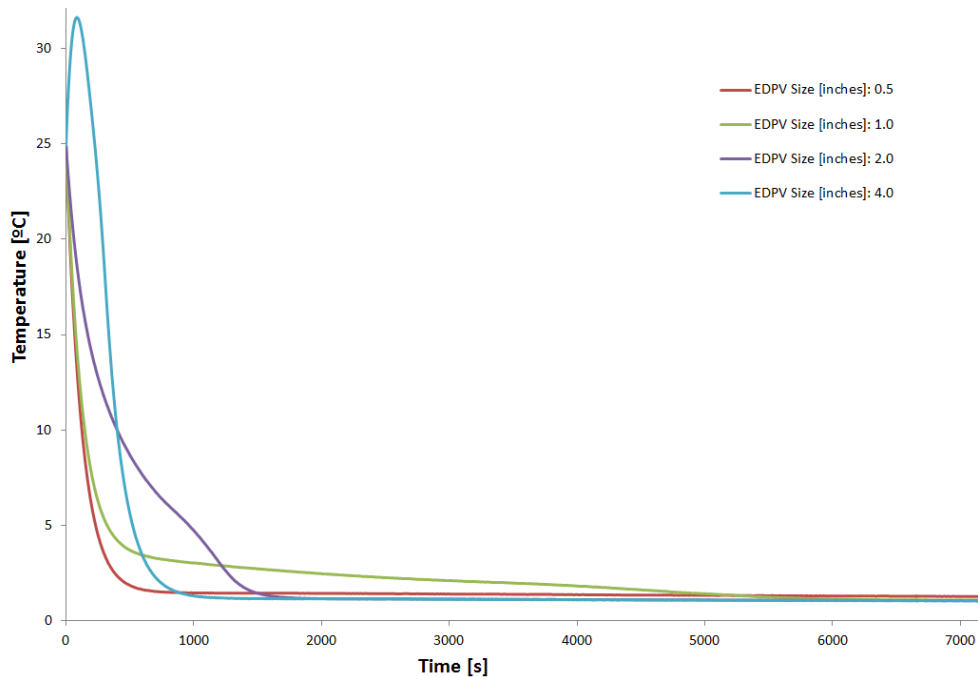
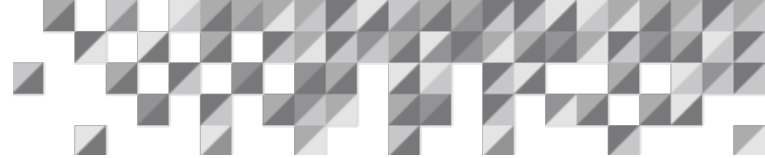


Figure 12: Fluid and Wall Differential Temperature History (10% Liquid Level)

### Impact of Insulation Thickness

This sensitivity analysis examines the impact of four (4) different thermal insulation thicknesses (0", 2", 7", and 14"), evaluated at three (3) different initial liquid levels (10%, 50%, and 90%).

As shown in Figures 13 through 15, the presence of insulation in cold depressurization inhibits effective heat transfer between the vessel wall and the surrounding. The impact of insulation is, however, not significant. Notice the metal temperature difference between the case of no insulation and one with 2". In all cases, the difference is less than a fifth of a degree. The results also show that the insulation thickness impact is further reduced at higher initial liquid levels.

In the event of a non-fired depressurization, it can be concluded that no insulation is generally preferred; this is the opposite of an external fire scenario. In the event of fire, insulation has been found to be one of the few effective mitigation<sup>2</sup> measures, preventing heat transfer from the fire to the vessel wall. Since insulation has minimal impact on a cold depressurization and provides effective mitigation for an external fire, it should be seriously considered when sizing an EDPV for both scenarios.

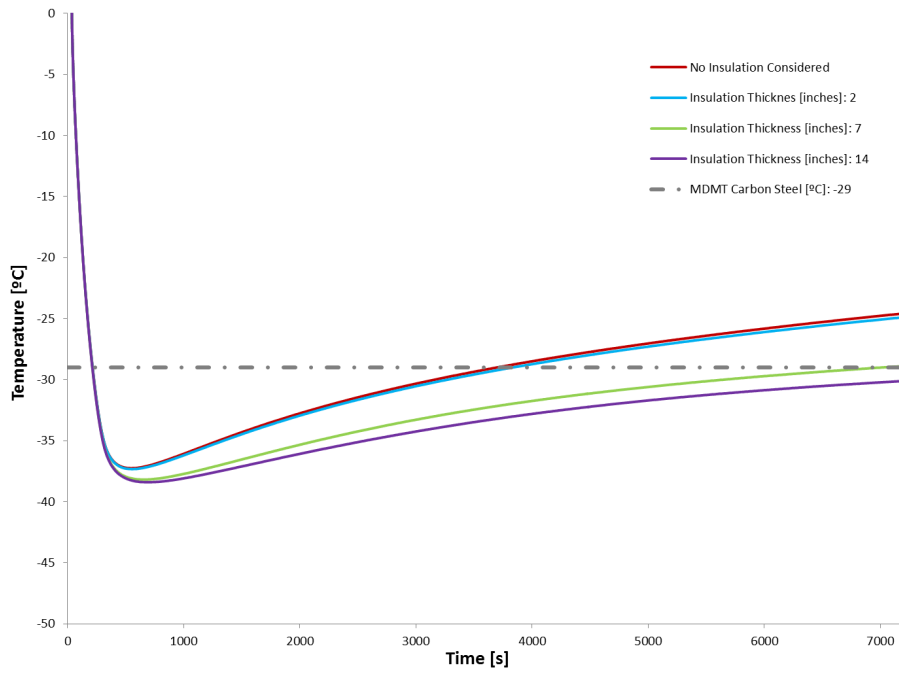
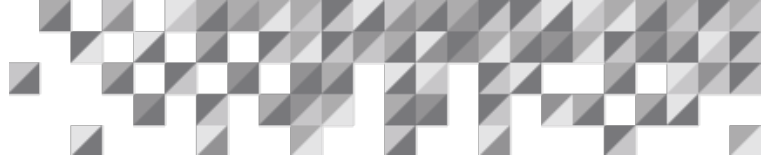


Figure 13: Wall Temperature History (Insulation Impact; 10% liquid level; EDPV size 4")

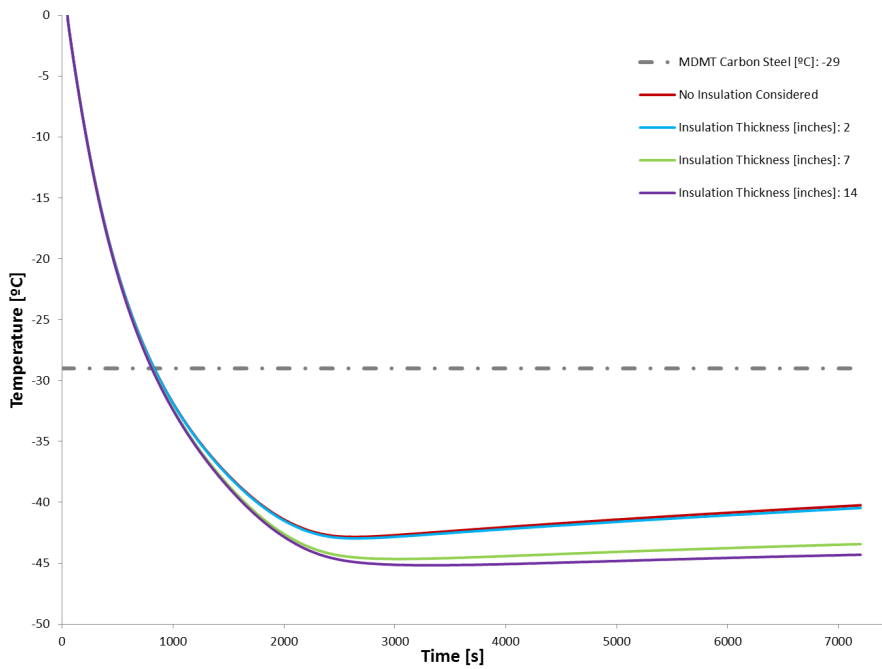


Figure 14: Wall Temperature History (Insulation Impact; 50% liquid level; EDPV size 2")

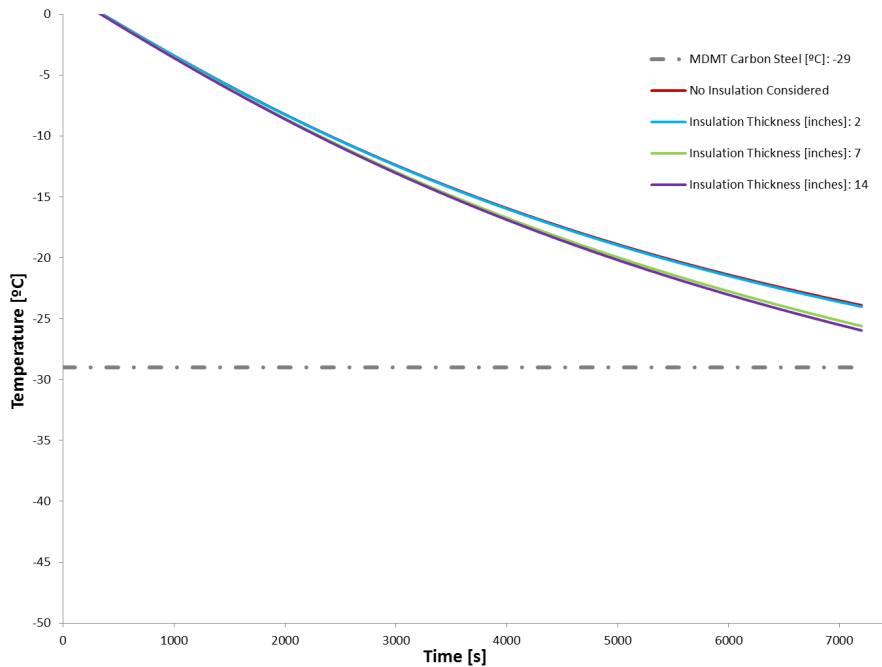
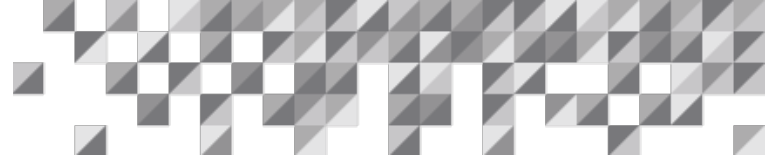


Figure 15: Wall Temperature History (Insulation Impact; 90% liquid level; EDPV size 0.5")

### Impact of Fluid Compositions

This sensitivity analysis examines the impact of six (6) different methane fluid compositions (0.05, 0.10, 0.20, 0.30, 0.4, and 0.50), starting at 22.5 barg, a 10% initial liquid level, and with a 2" EDPV.

Figures 16 and 17 show both the pressure and wall temperature histories at different methane compositions. Note that the temperature profiles are based on the bottommost segment of the vessel, assessing the metal wall in direct contact with liquid. The results indicate that while a richer methane content would help depressurize more rapidly, it also accelerates the cryogenic liquid heat transfer to the metal wall. At a methane mole fraction of 0.4 or higher, the metal wall temperature falls below  $-29^{\circ}\text{C}$ , lower than the normal MDMT desired for carbon steel. This implies that a higher methane content may pose a greater risk of material embrittlement.

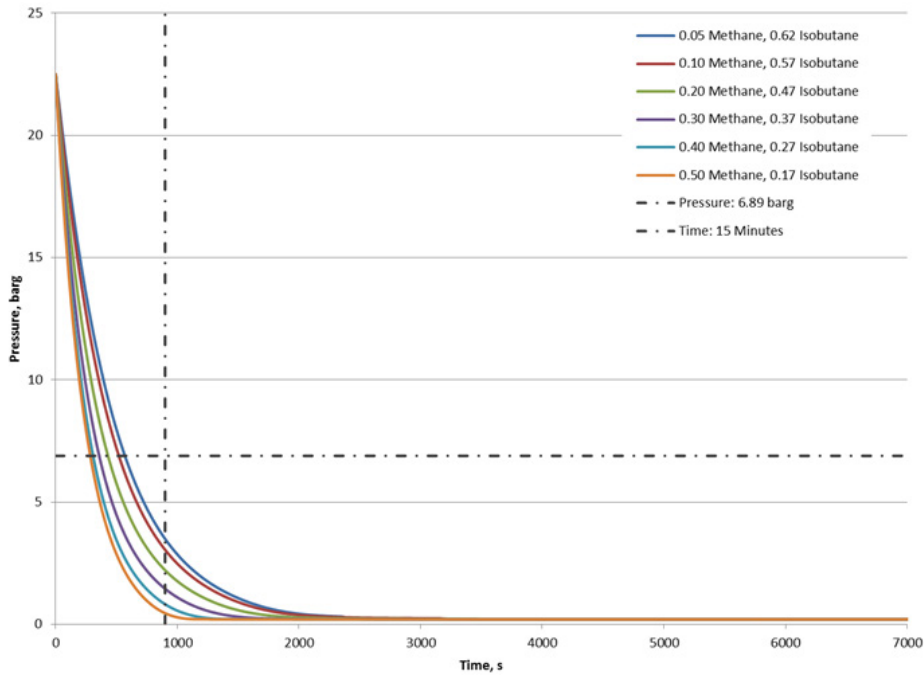
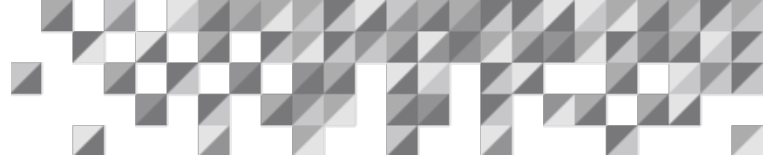


Figure 16: Pressure History (Methane Composition Impact; 10% liquid level; EDPV size 2")

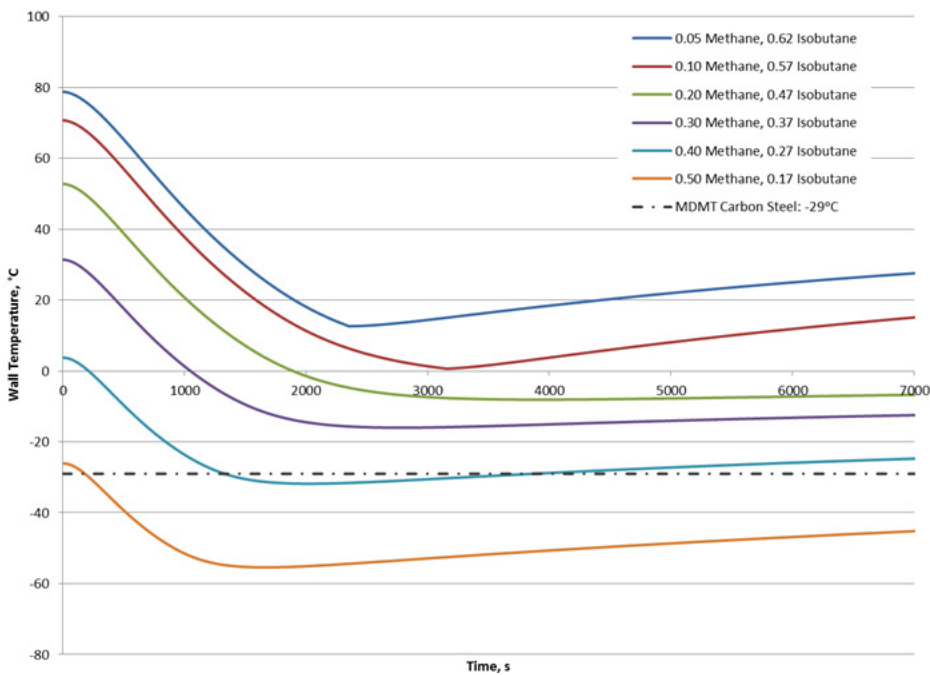
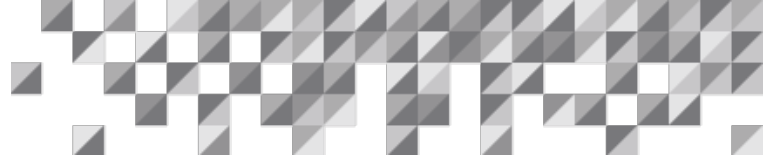


Figure 17: Wall Temperature History (Methane Composition Impact; 10% liquid level; EDPV size 2")



## Conclusions

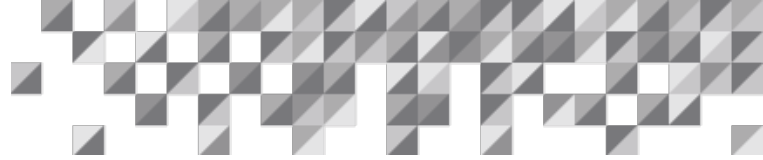
The vessel segmentation used in this paper demonstrates a reliable approach for modeling detailed vessel wall dynamics. Due to the direct contact between the metal wall and the cryogenic fluid, the probability of embrittlement failure is higher at the bottom portion of the vessel during a cold LNG depressurization. A lower initial filled level would typically lessen the risk of material embrittlement. A larger depressurizing rate, on the other hand, would exacerbate the cryogenic effect, causing a lower metal temperature. For that reason, while a sufficiently large EDPV size is required for depressurization within the specified pressure and time criteria, an oversized EDPV is generally not advised.

In the event of a non-fired depressurization, no thermal insulation is generally more preferred. This is the opposite of an external fire scenario, where insulation<sup>2</sup> has been found to be one of the few effective mitigations. Since insulation has minimal impact on a cold depressurization and provides an effective mitigation measure for an external fire, it should be seriously considered when sizing for both scenarios.

The sensitivity analysis on the methane fluid compositions indicates that while a richer methane content would help depressurize more rapidly, it also accelerates the cryogenic liquid heat transfer to the metal wall. This implies that a higher methane content may pose a greater risk of material embrittlement.

The thickness of the vessel can significantly influence wall temperatures. A thinner vessel thickness generally results in lower wall temperatures, exposing the equipment to a higher risk of brittle failure.

During the project phase, material of construction should be carefully selected, accounting for the vapor pressure of the fluid mixture whenever a cold depressurization is expected.



## References

- [1] Melhem, A. G., “Properly Calculate Vessel and Piping Wall Temperatures During Depressurizing and Relief,” published online 2014; DOI 10.1002/prs. 11689
- [2] American Petroleum Institute, “Pressure Relieving and Depressurizing Systems”, ANSI/API Standard 521, Sixth Edition, 2013
- [3] Salater, P., et al., “Size Depressurization and Relief Devices for Pressurized Segments Exposed to Fire,” Chemical Engineering Progress, September 2002
- [4] Overa, S., et al., “Determination of Temperatures and Flare Rates During Depressurization and Fire,” Presented at 72<sup>nd</sup> Annual GPA Convention, San Antonio, Texas, March 15-17, 1993