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Wall Dynamics Tutorial

Marcel Amorós-Martí
Director, California Office Lead
amoros.m.ca@iomosaic.com

ANAB ACCREDITED ISO/IEC 17025 TESTING LABORATORY

TÜV NORD TÜV USA Inc. ISO 9001

Marcel Amorós-Martí – Director, California Office Lead ioMosaic Corporation

- B.S. and M.S. in Chemical Engineering
- Technical Expertise includes:
  - Pressure Relief and Flare Systems (PRFS)
  - Consequence Analysis
  - Facility Siting and Quantitative Risk Assessment (QRA)
  - Process Safety Management (PSM)
  - Process Hazard Analysis (PHA)
  - Layer Of Protection Analysis (LOPA)
  - Design and Verification of Safety Instrumented Systems (SIS)
- Contact Information: amoros.m.ca@iomosaic.com

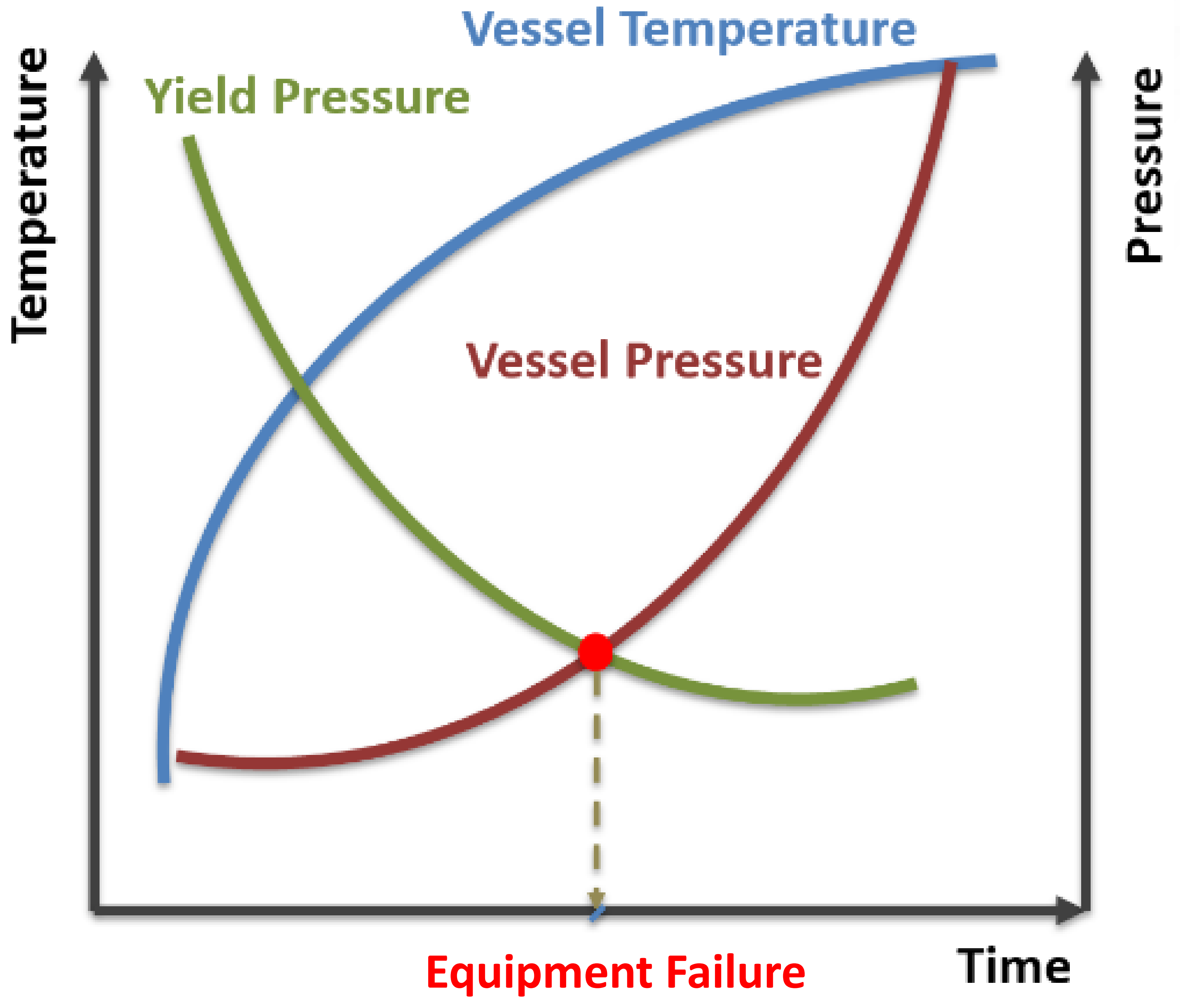
The purpose of this presentation is to address the following topics

- Evaluation of vessel and piping wall temperatures using the fundamental heat transfer equation outlined in API Standard 521
- Advantages and characteristics of the wall segmentation approach implemented in Process Safety Office® SuperChems™
- Application of the wall dynamics approach in SuperChems™ via 2 case studies
  - Case 1 – Pressure Vessel
  - Case 2 – Low-pressure Atmospheric Tank

Wall Dynamics Approach Basis

A typical scenario that is almost always considered is the exposure of an equipment to a flame jet or pool fire

- Process vessels and piping components may fail because of excessive deviations in internal or external pressure, and/or wall temperatures
  - Equipment wall temperature increases
  - Yield and tensile strength of the vessel walls decrease
  - Resistance to internal pressure decreases while pressure vessel increases



Source: ioMosaic Corporation

The fundamental heat transfer equation outlined in API Standard 521 is the basis for the wall dynamics approach

$$q_{absorbed} = \sigma(\alpha_{surface} \times \varepsilon_{fire} \times T_{fire}^4 - \varepsilon_{surface} \times T_{surface}^4) + h(T_{gas} - T_{surface})$$

- $q_{absorbed}$ is the absorbed heat flux from the fire, in W/m^2
- σ is the Stefan-Boltzman constant, which is 5.67x10^{-8} W/m^{2}K^4
- $\alpha_{surface}$ is the equipment absorptivity, dimensionless
- ε_{fire} is the fire emissivity, dimensionless
- T_{fire} is the fire temperature, in K
- $\varepsilon_{surface}$ is the equipment emissivity, dimensionless
- $T_{surface}$ is the equipment temperature, in K
- h is the convection heat transfer coefficient of air/fire in contact with the equipment, in W/m^{2}K
- T_{gas} is the temperature of air/fire in contact with the equipment surface, in K

Source: API Standard 521, 2020, "Pressure-relieving and Depressuring Systems", 7th Edition

API Standard 521 provides recommended values for jet fires when data is not available

		Flame Jet			
Parameter	Description	Surface Average Heat Flux		Local Peak Heat Flux	
Leak rates		>2 kg/s (Large Jet)	≤2 kg/s (Small Jet)	>2 kg/s (Large Jet)	≤2 kg/s (Small Jet)
ε_f	Flame emissivity	0.33	NA	0.87	0.75
ε_w	Wall emissivity	0.75	NA	0.75	0.75
α_w	Wall absorptivity	0.75	NA	0.75	0.75
h	Convective heat transfer coefficient between equipment and surrounding air	40 W/m^2 K	NA	100 W/m^2 K	90 W/m^2 K
T_g	Temperature of combustion gases flowing over the surface	1,173 K (900°C)	NA	1,473 K (1,200°C)	1,373 K (1,100°C)
T_f	Fire temperature	1,373 K (1,100°C)	NA	1,473 K (1,200°C)	1,373 K (1,100°C)
q_f	Fire heat flux	100 kW/m^2	NA	350 kW/m^2	250 kW/m^2
q_w	Absorbed heat flux	85 kW/m2	NA	290 kW/m^2	210 kW/m^2

Source: API Standard 521, 2020, "Pressure-relieving and Depressuring Systems", 7th Edition

API Standard 521 also provides recommended values for open pool fires when data is not available

Parameter	Description	Pool Fire: Surface Average Heat Flux	Pool Fire: Local Peak Heat Flux
ε_f	Flame emissivity	0.75	0.75
ε_w	Equipment emissivity	0.75	0.75
α_w	Equipment absorptivity	0.75	0.75
h	Convective heat transfer coefficient between equipment and surrounding air	20 W/m^2 K	20 W/m^2 K
T_g	Temperature of combustion gases flowing over the surface	873 K (600°C)	1,323 K (1,050°C)
T_f	Fire temperature	1,023 K (750°C)	1,323 K (1,050°C)
q_f	Fire heat flux	60 kW/m^2	150 kW/m^2
q_w	Absorbed heat flux	45 kW/m2	120 kW/m^2

Source: API Standard 521, 2020, "Pressure-relieving and Depressuring Systems", 7th Edition

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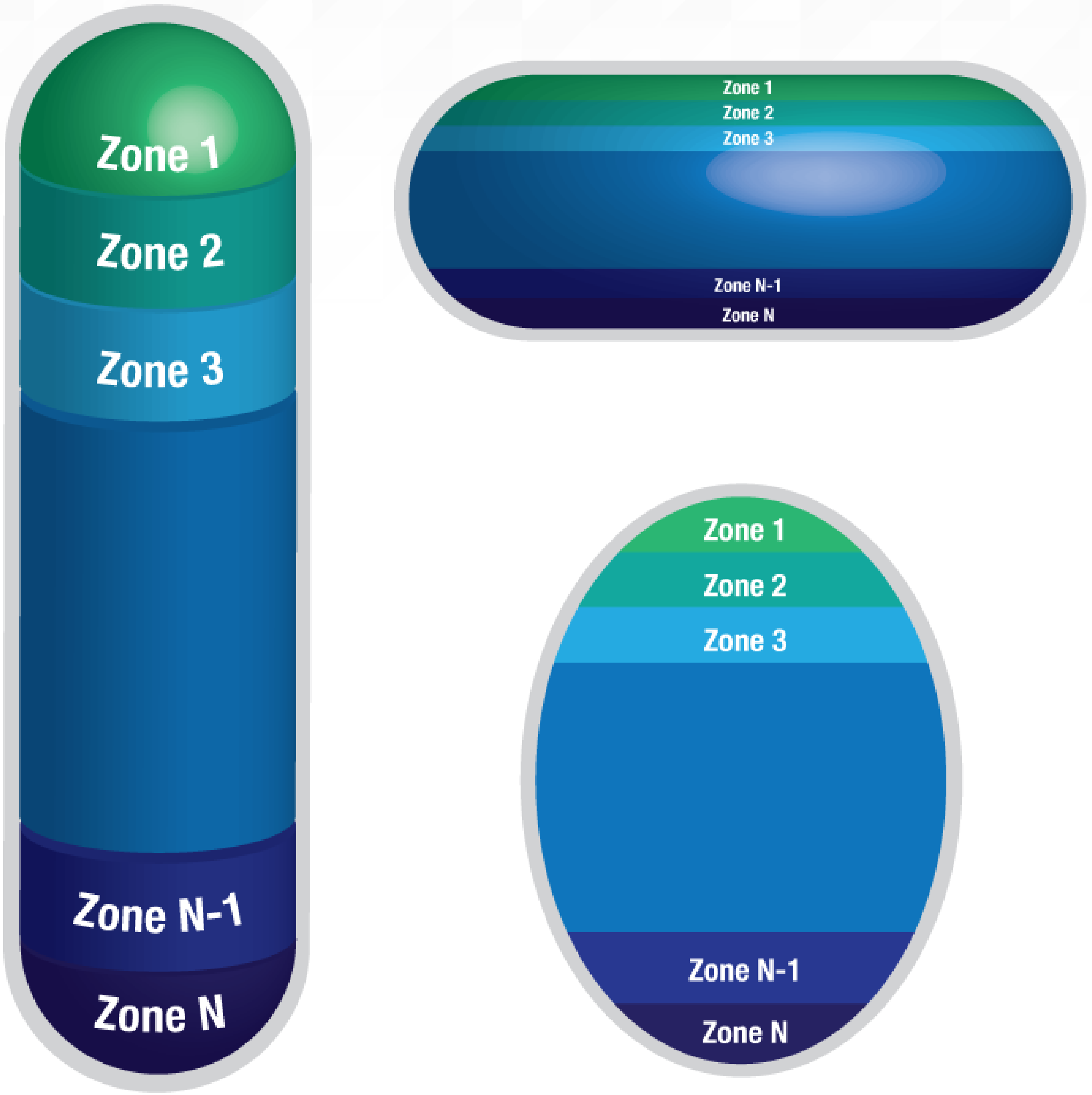
Heat transfer is calculated as a function of time and includes several options

- Heat transfer phenomena is calculated as a function of time
  - From ambient to/from wall segment
  - From wall segment to wall segment
  - From wall segment to/from fluid
- Ambient to wall segment heat transfer options include insulation, solar heating, rain, water sprays, pool fires and jet fires
- Wall segment to fluid heat transfer include radiation, natural convection, forced convection, film boiling and pool boiling

A unique aspect of SuperChems™ is how a vessel is sliced into segments

- No limit to the number of segments that the user can define
- Allows modeling flame jet impingement, and/or the effect of an open pool fire in different vessel sections / segments
- Ability to represent a wide variety of vessel shapes and heads, including composite vessels



Source: Melhem, G.A., Gaydos, D., 2014, "Properly Calculate Vessel and Piping Wall Temperatures During Depressuring and Relief", Process Safety Progress (Vol. 34, No.1)

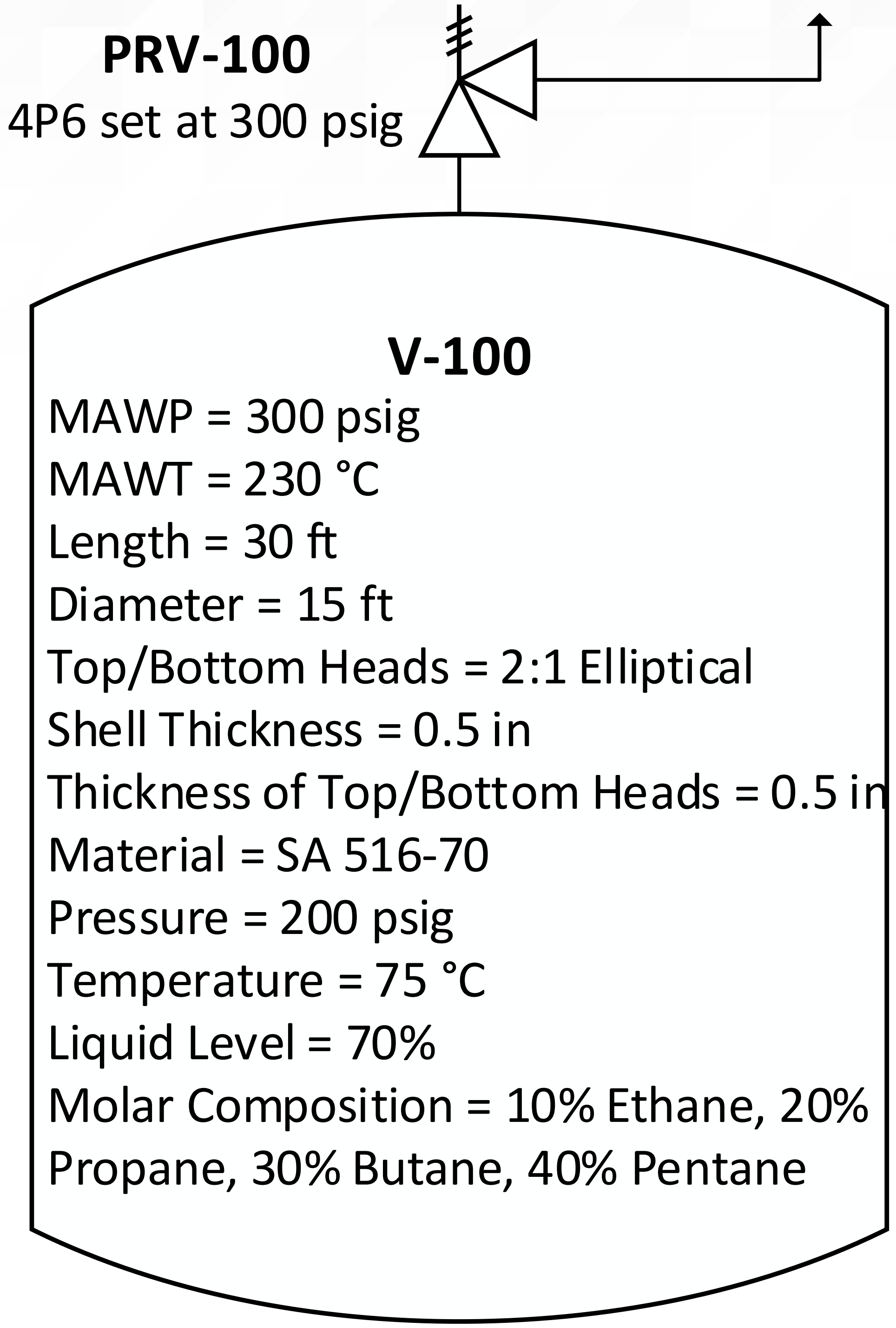
Wall dynamics approach in SuperChems™ is a very powerful tool

- Ability to predict the fluid dynamics of equipment containing liquids, vapors, and multiphase flows with or without chemical reactions
  - Including the Design Institute for Emergency Relief Systems (DIERS) technology to estimate vapor-liquid disengagement
- Ability to specify equipment internals using a variety of materials of construction
- Ability to connect multiple equipment and connect relief and process lines to the top and/or bottom of equipment
- Ability to include incoming and outgoing fluid streams

Case Studies in SuperChems™
Case 1 – Pressure Vessel

Vessel V-100 is protected by PRV-100 and exposure to an open pool fire has been identified as a contingency of concern

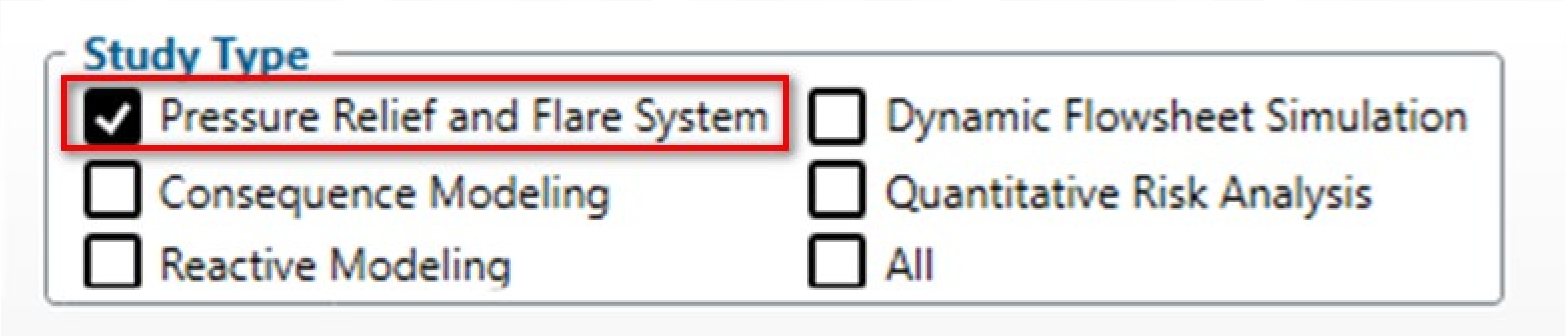
- Use of API Standard 521 recommended values for an open pool fire because no data is available on the pool fire characteristics
- The properties of the vessel and relief device under analysis are illustrated to the right
- SuperChems™ new visual interface is used to model this system

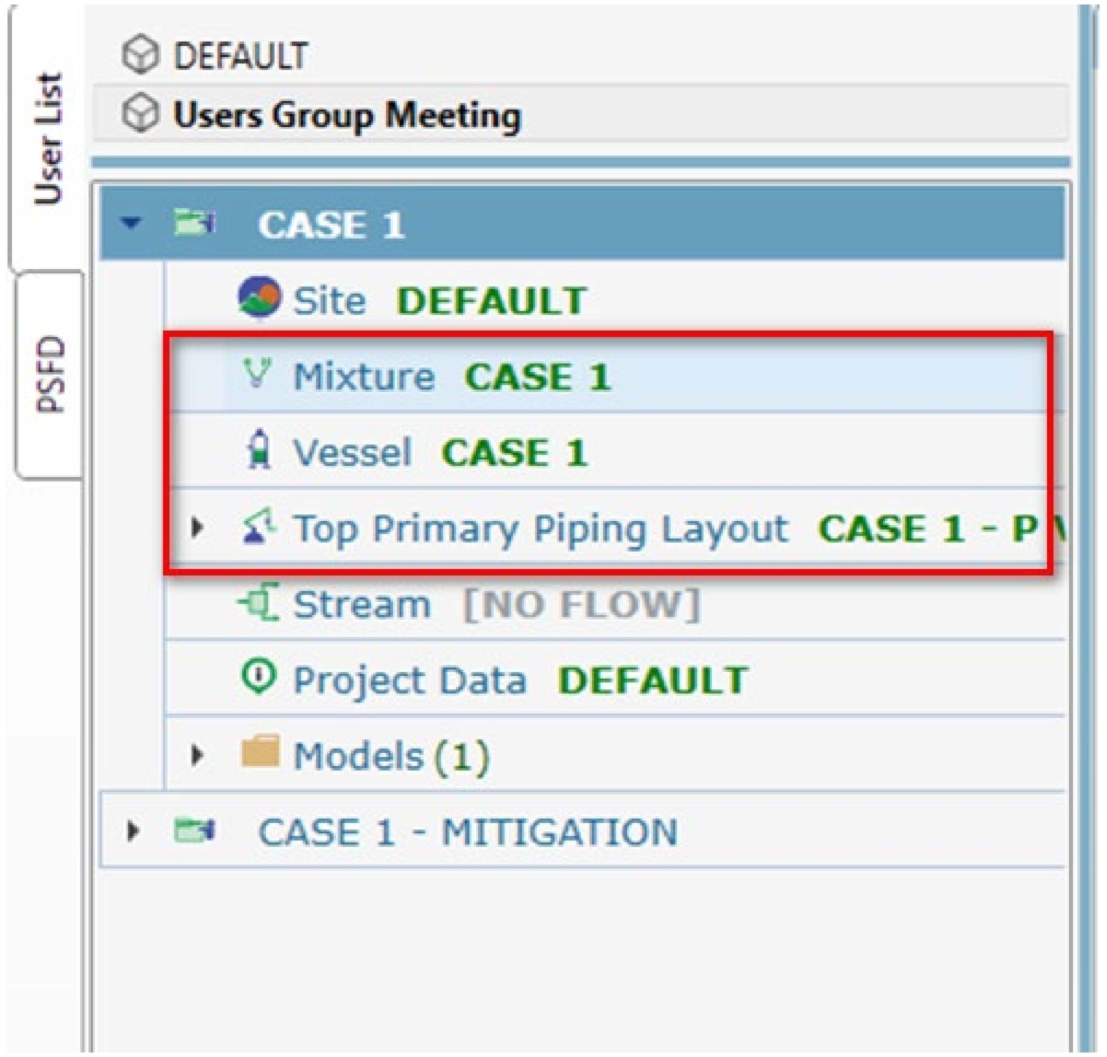


Source: ioMosaic Corporation

What are the necessary objects in SuperChems™?

- Under options, select the applicable "Study Type"
  - For this type of analysis, select "Pressure Relief and Flare System"
- Next, create 1 Scenario and name it appropriately
- 6 objects will appear under Case 1 scenario:
  - For this type of calculation, we only need the following objects: Mixture, Vessel, Piping Layout, and Pressure Relief Valve

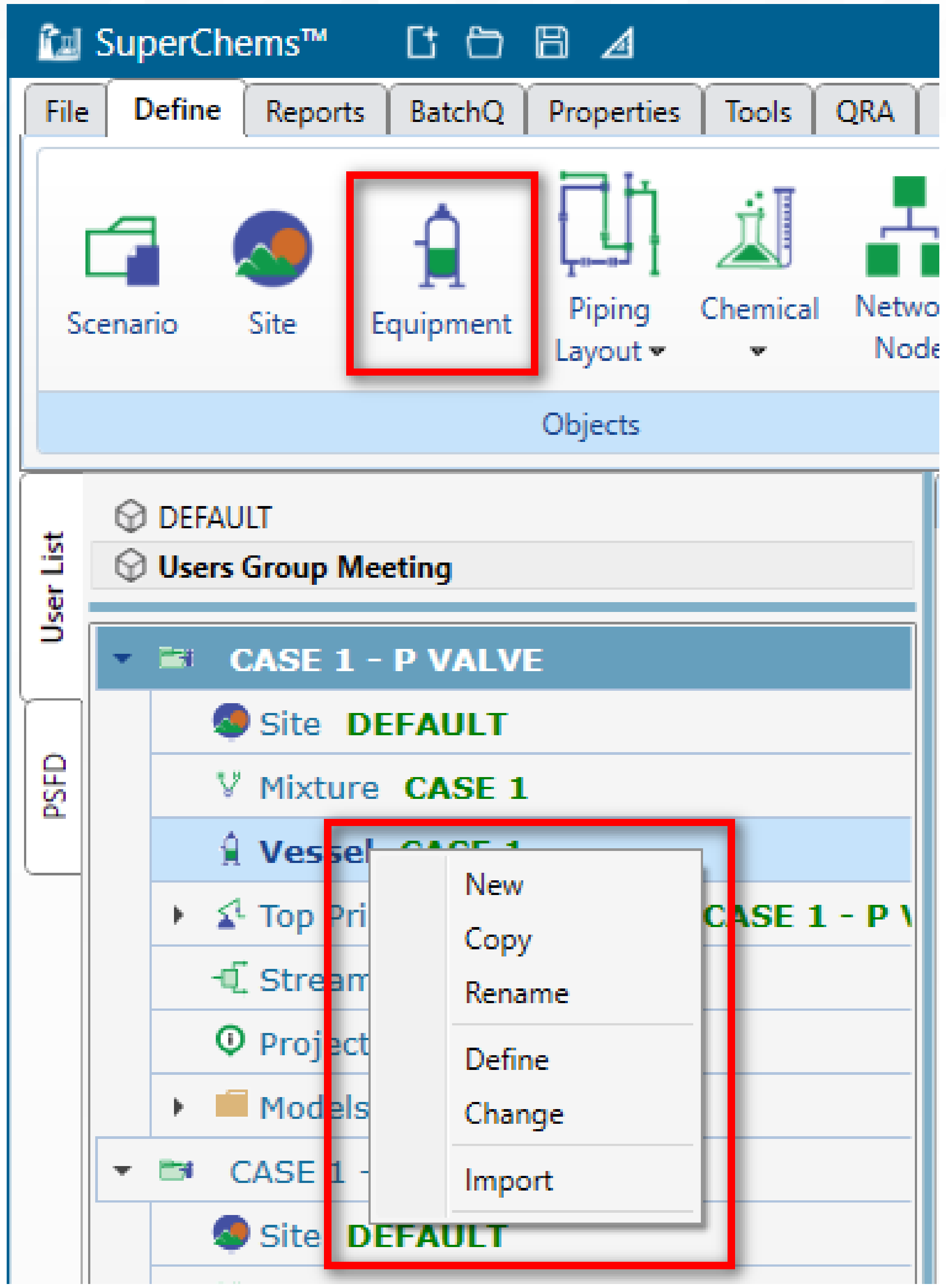




Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

How should a vessel be defined?

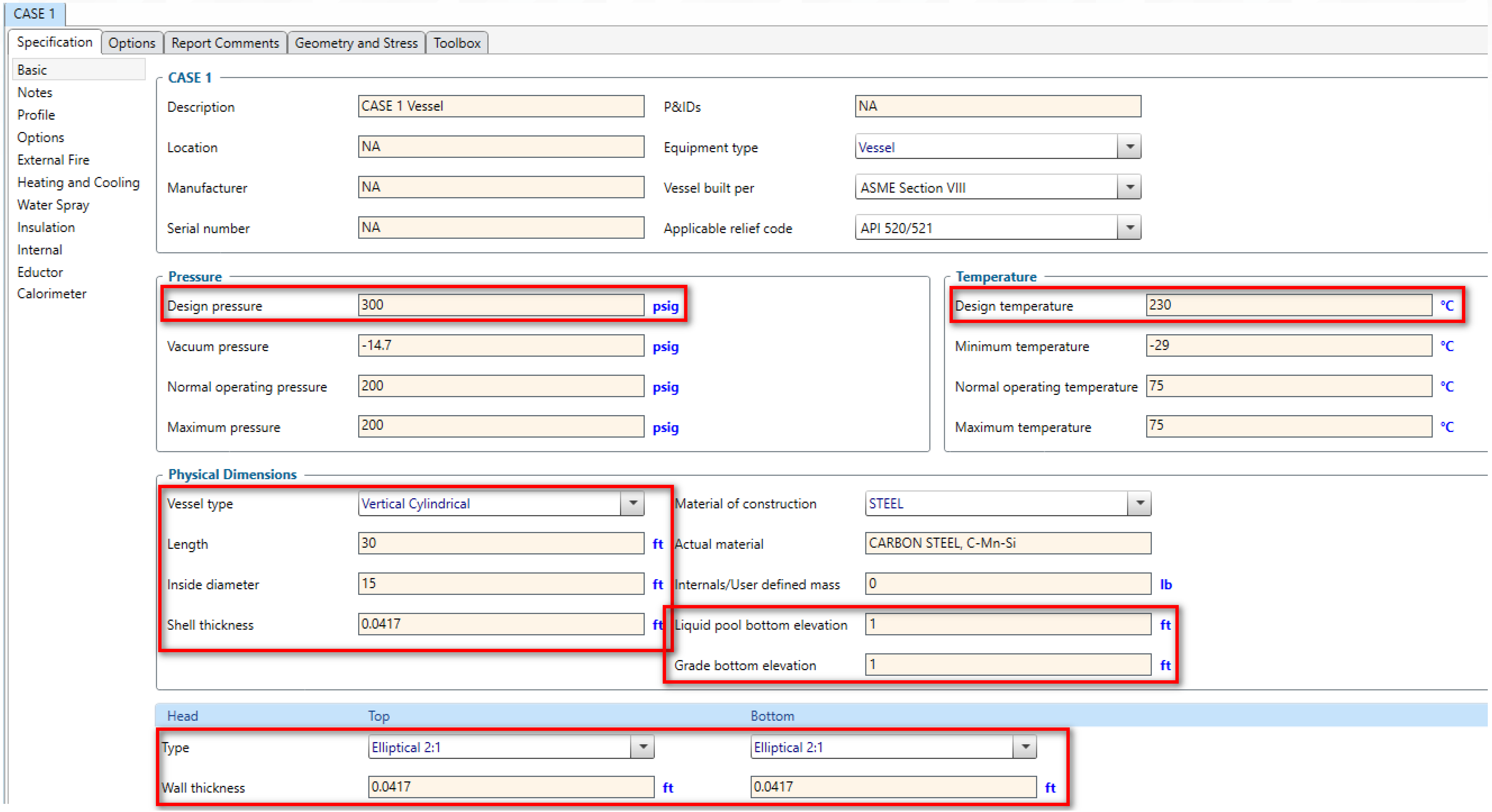
- Right click under “Vessel”, select “New”, and name the Vessel appropriately
  - Note that SuperChems^{TM} will automatically assign the new vessel to the scenario of interest
- Other options include:
  - Copy, Rename, Define, Change, Import
- A vessel can also be defined under “Define” tab at the top, and selecting “Equipment”



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

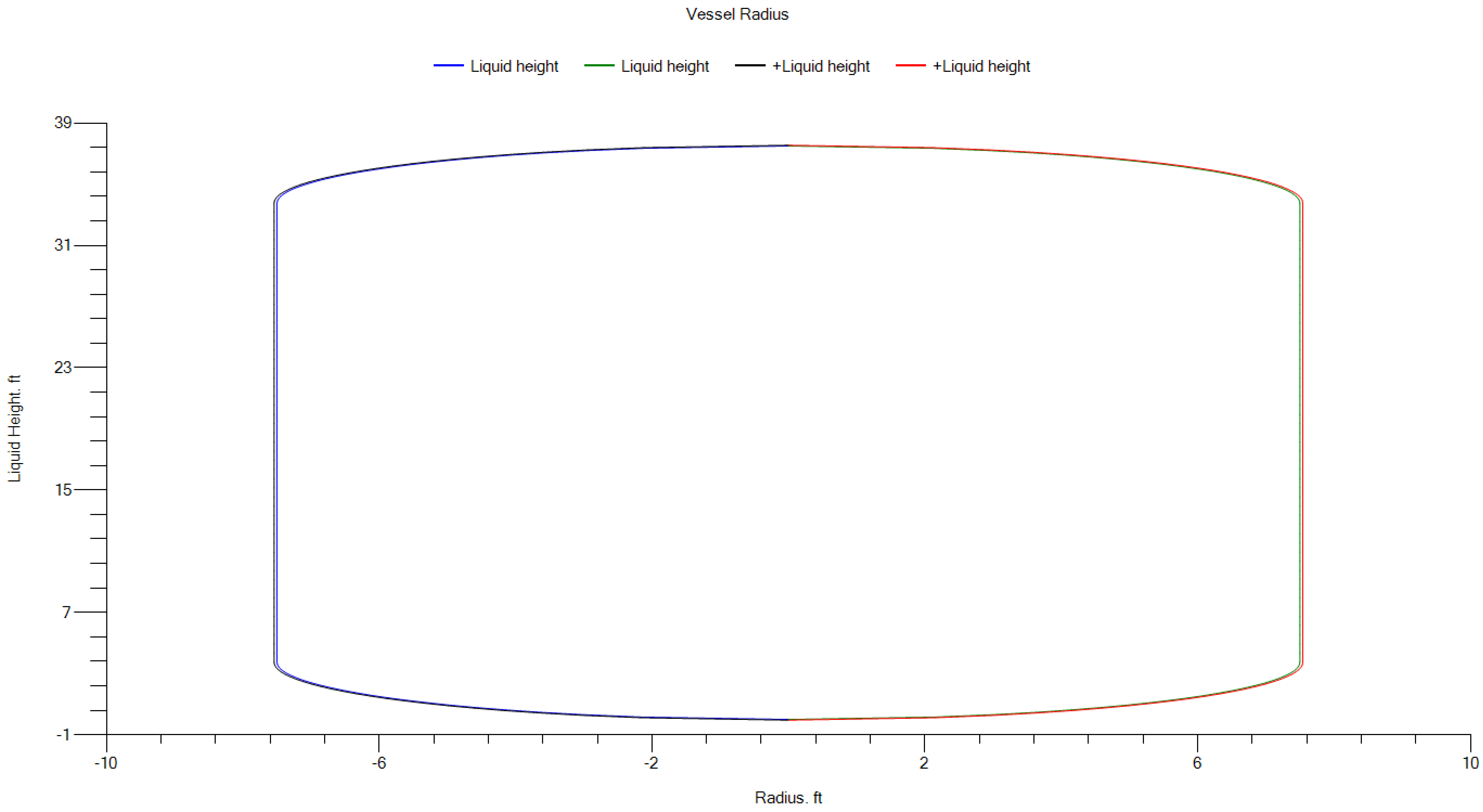
What are the necessary specifications?

- Design pressure
- Design Temperature
- Vessel Type
- Length
- Inside Diameter
- Shell Thickness
- Elevation
- Head Type
- Wall Thickness



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

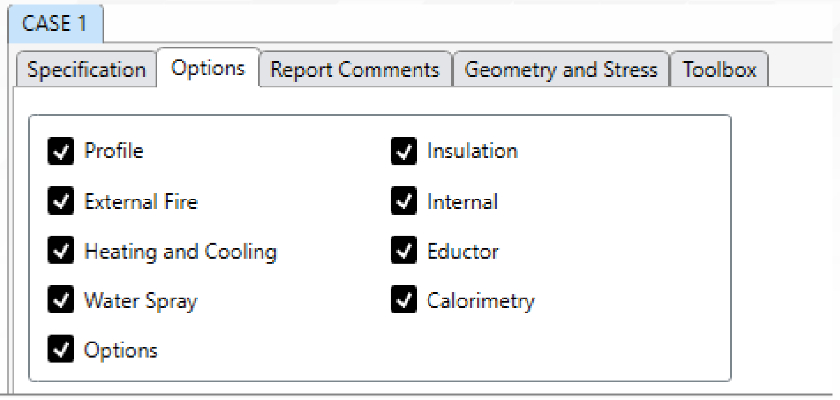
Always check the vessel geometry under "Geometry and Stress" tab to ensure the vessel dimensions

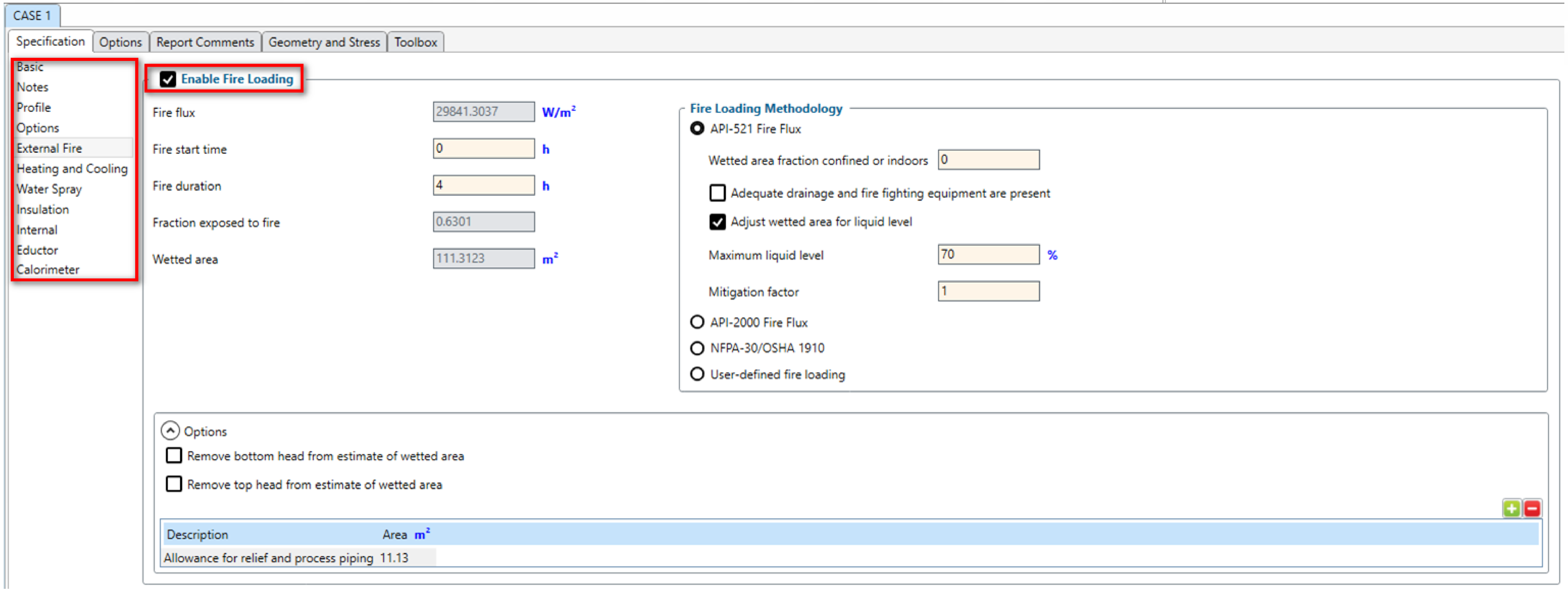


Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Vessel specification tabs appear based on the options selected

- To perform the wall dynamics, check "Enable Fire Loading"

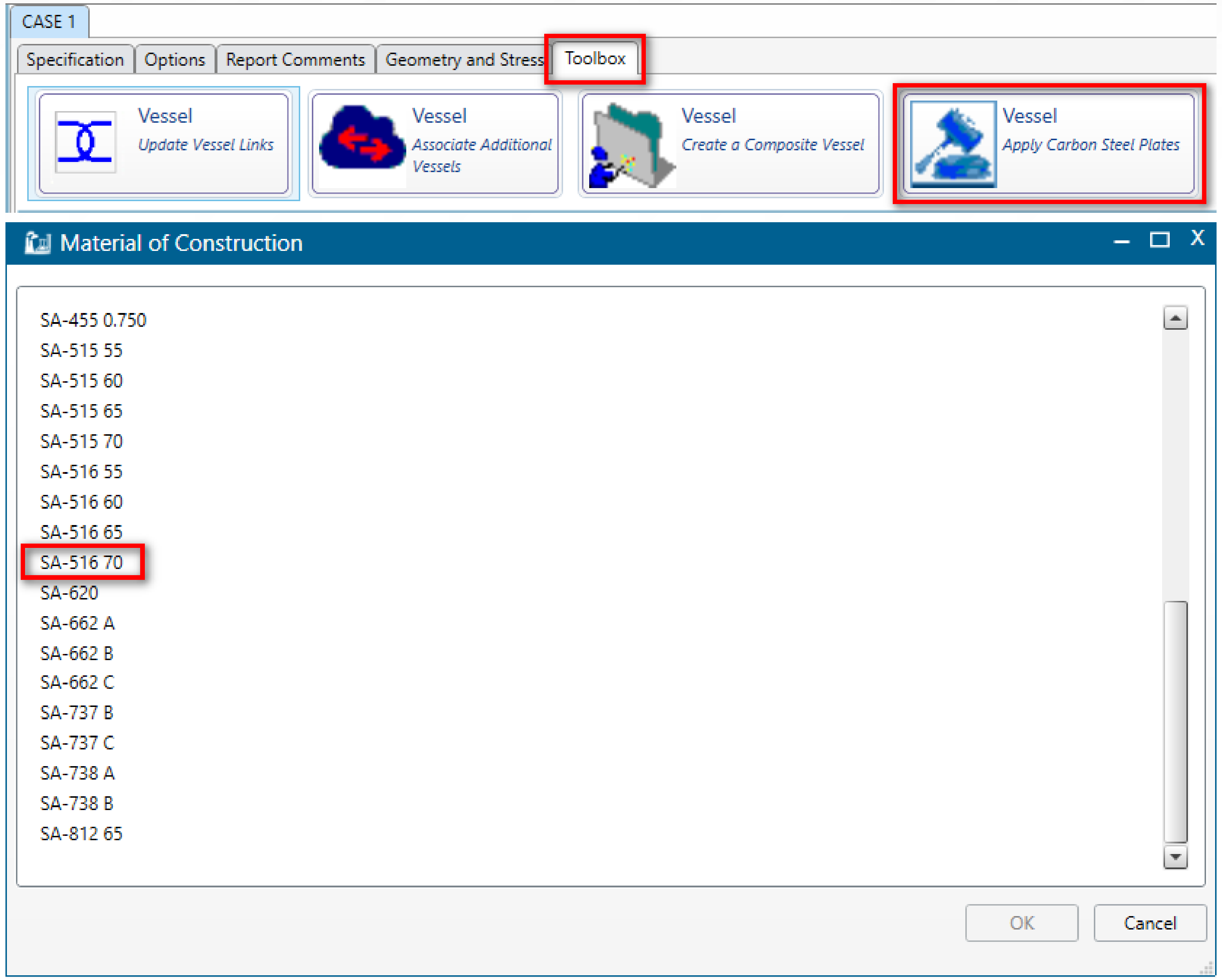




Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Apply the appropriate Carbon Steel Plate and Allowable Stress Curve

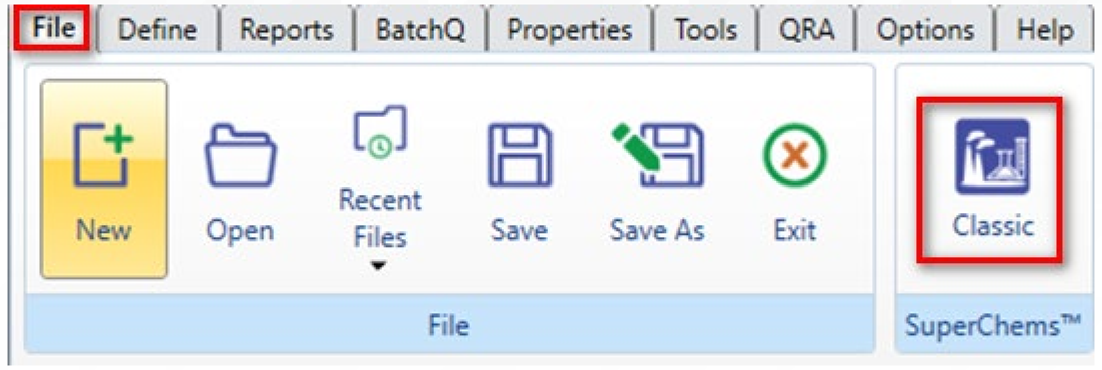
- Go to "Toolbox" tab, and click the icon "Vessel, *Apply Carbon Steel Plates*"
- SuperChems™ has prepopulated several carbon steel plate and allowable stress curves
- In this example, SA-516 Grade 70 Carbon Steel is applied based on the vessel material of construction

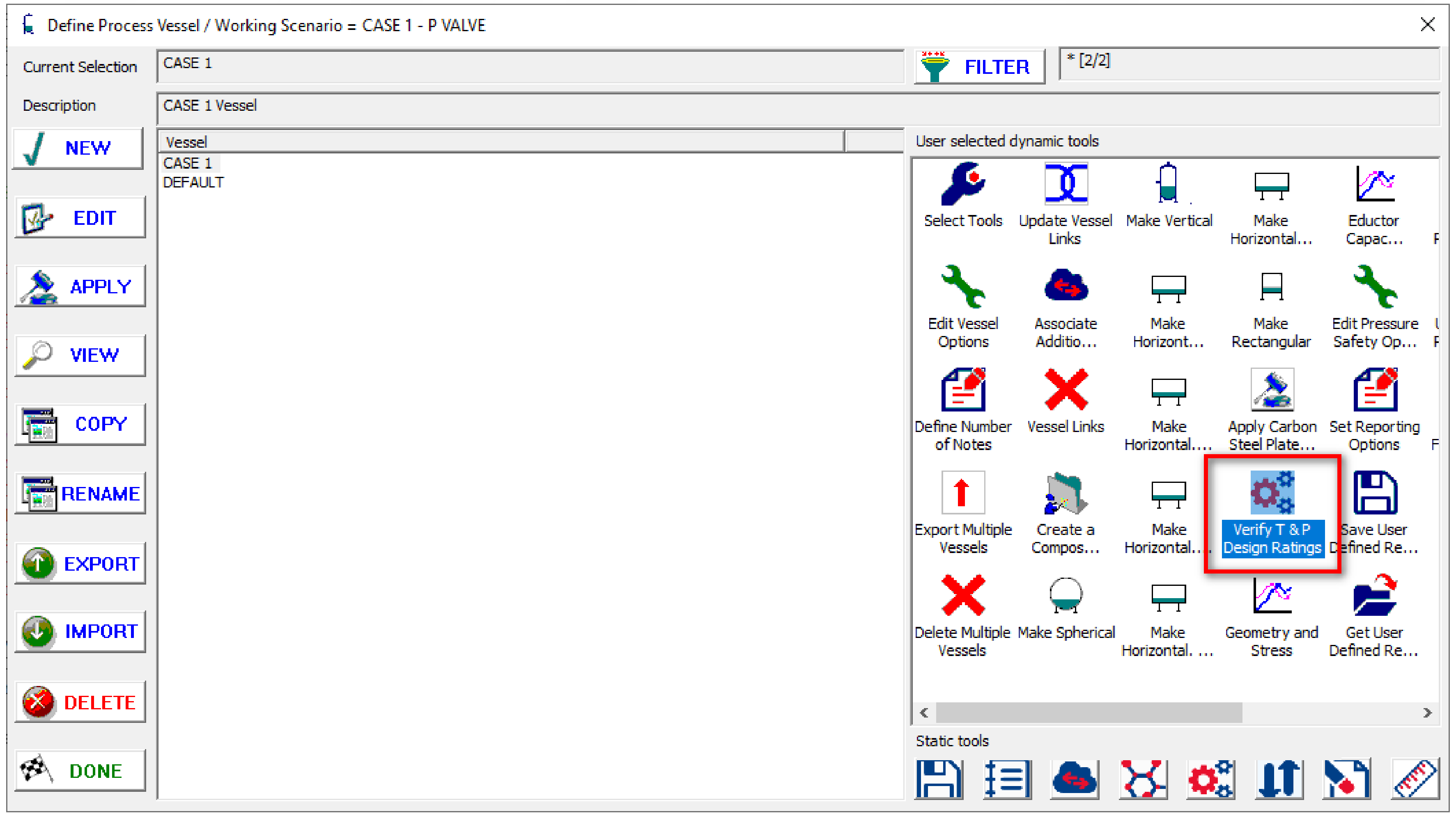


Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Temperature and pressure ratings can be verified by switching to SuperChems™ classic

- Under “File” tab, click the “Classic” icon
- Under the Vessel object, click the “Verify T&P Design Ratings” icon





Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

ioMosaic uses 2/3 of the Ultimate Tensile Strength (UTS) as a conservative limit based on NFPA 68 Section 5.3.3.1

Vessel Name	CASE 1
Vessel Type	Vertical Cylindrical; User defined heads
Vessel Top Head Type	Elliptical 2:1
Vessel Bottom Head Type	Elliptical 2:1

** METERIAL OF CONSTRUCTION SPECIFICATIONS. OBTAIN THIS INFORMATION FROM ASME TABLES

Actual Material of Construction Description	CARBON STEEL, C-Mn-Si	
Databank material of construction used for thermal	STEEL	STEEL
Specification	SA-516	
P-No, G-No, or S-No	P1, G2	
Product Form	Steel Plate or Sheet	
Grade	70	
Note 1	See Note 17 in ASME Boiler and Pressure Vessel Code. Page 280	
Note 2	External pressure chart 5-UCS-28.2	
Minimum Temperature. °C	-28.89	
Minimum yield strength. psia	38000.00	
Minimum tensile strength. psia	70000.00	

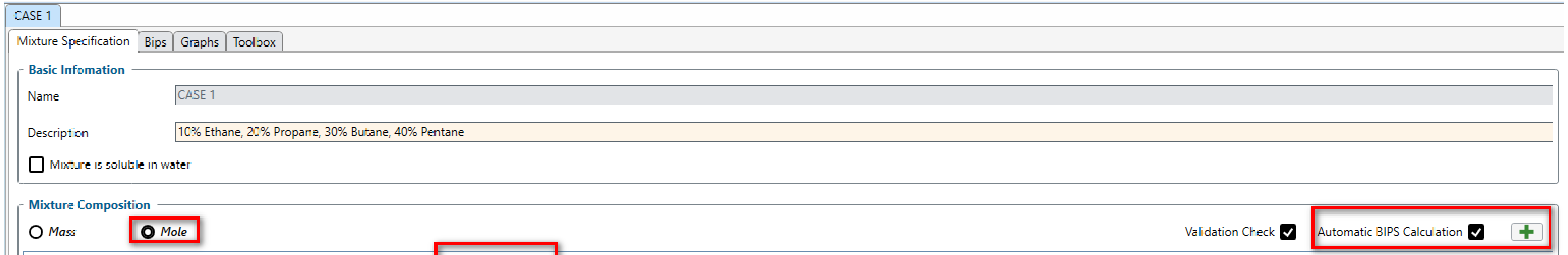
Allowable Stress Basis	ASME												
Temperature. °C	-28.89	343.33	371.11	398.89	426.67	454.44	482.22	510.00	537.78				
Allowable Stress. psia	1.750E+04	1.750E+04	1.660E+04	1.480E+04	1.200E+04	9.300E+03	6.500E+03	4.500E+03	2.500E+03				
Young's Modulus of Elasticity. psia	3.410E+07	3.178E+07	3.119E+07	3.054E+07	2.985E+07	2.911E+07	2.832E+07	2.791E+07	2.748E+07	2.704E+07	2.659E+07	2.613E+07	2.565E+07
Coefficient of Linear Thermal Expansion. /°C	7.387E-06	1.507E-05	1.590E-05	1.665E-05	1.733E-05	1.795E-05	1.850E-05	1.876E-05	1.900E-05	1.922E-05	1.943E-05	1.963E-05	1.982E-05
Poisson's Ratio	0.290	0.290	0.290	0.290	0.290	0.290	0.290	0.290	0.290	0.290	0.290	0.290	0.290

Failure Stress Basis	2/3 UTS												
Temperature. °C	-253.889	37.778	93.333	148.889	204.444	260.000	315.556	343.333	371.111	398.889	426.667	454.444	482.222
Failure Stress. psia	46666.667	46666.667	46666.667	46666.667	44151.697	41357.285	39121.756	38283.433	37724.551	37165.669	36327.345	35768.463	33253.493

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Defining a mixture object

- Select the basis (Mass or Mole), and then add components by clicking the green button
  - Note that if the "Automatic BIPS Calculation" option is selected, SuperChems™ will automatically apply the Binary Interaction Parameters (BIPS) for us



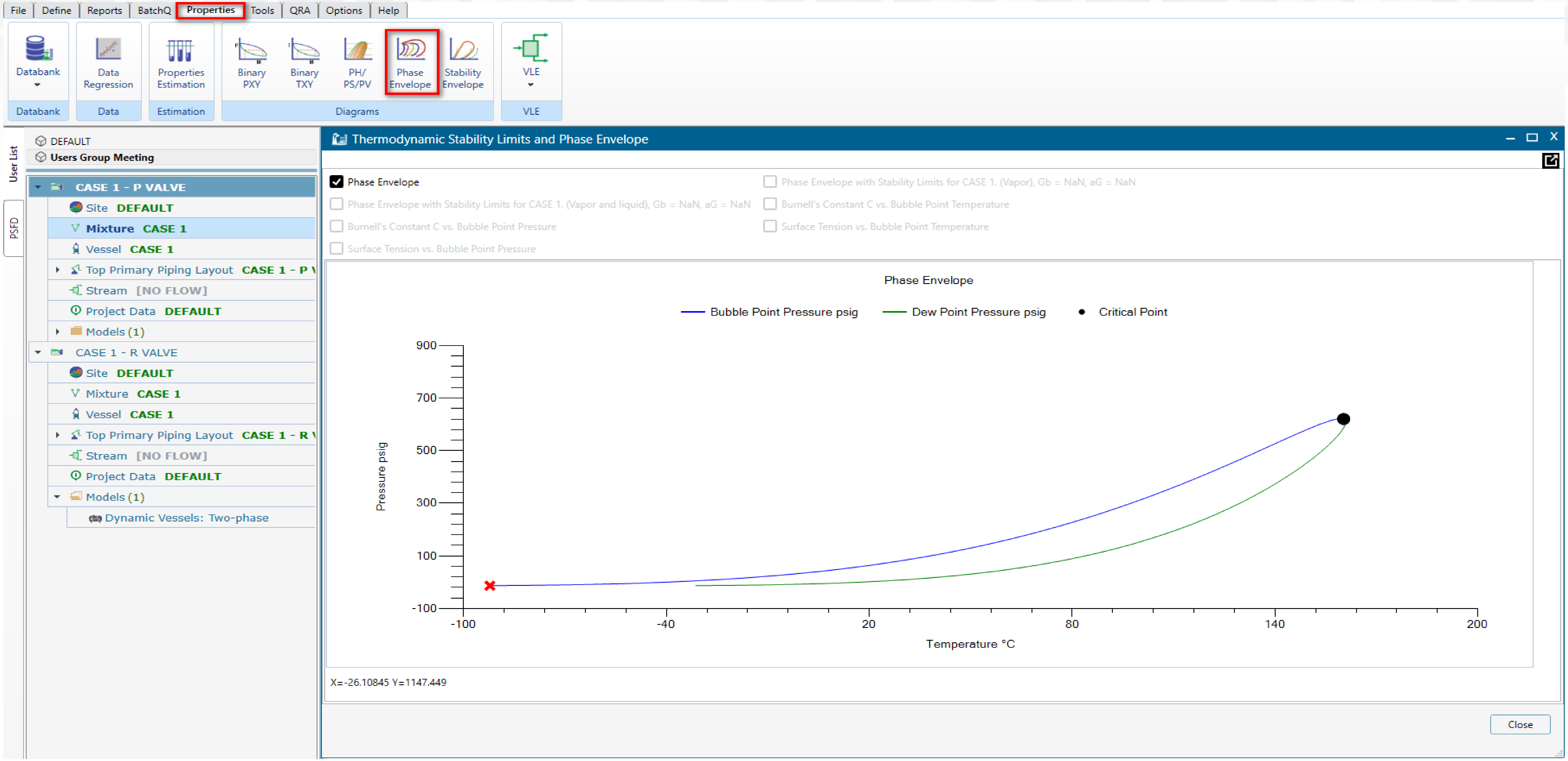
Compound	Formula	ID	MW	Mass Fraction	Mole Fraction	User Composition
ETHANE	C2H6	1	30.070	0.0517	0.1000	0.1000
PROPANE	C3H8	2	44.097	0.1517	0.2000	0.2000
n-BUTANE	C4H10	3	58.123	0.3000	0.3000	0.3000
n-PENTANE	C5H12	4	72.150	0.4965	0.4000	0.4000

Kij	ETHANE	PROPANE	n-BUTANE	n-PENTANE
ETHANE	0	0.00137	0.00706	0.0072
PROPANE	0.00137	0	0.00142	0
n-BUTANE	0.00706	0.00142	0	0
n-PENTANE	0.0072	0	0	0

Lij	ETHANE	PROPANE	n-BUTANE	n-PENTANE
ETHANE	0	-0.01489	-0.02206	0.0016
PROPANE	0.01489	0	-0.03814	0
n-BUTANE	0.02206	0.03814	0	0
n-PENTANE	-0.0016	0	0	0

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

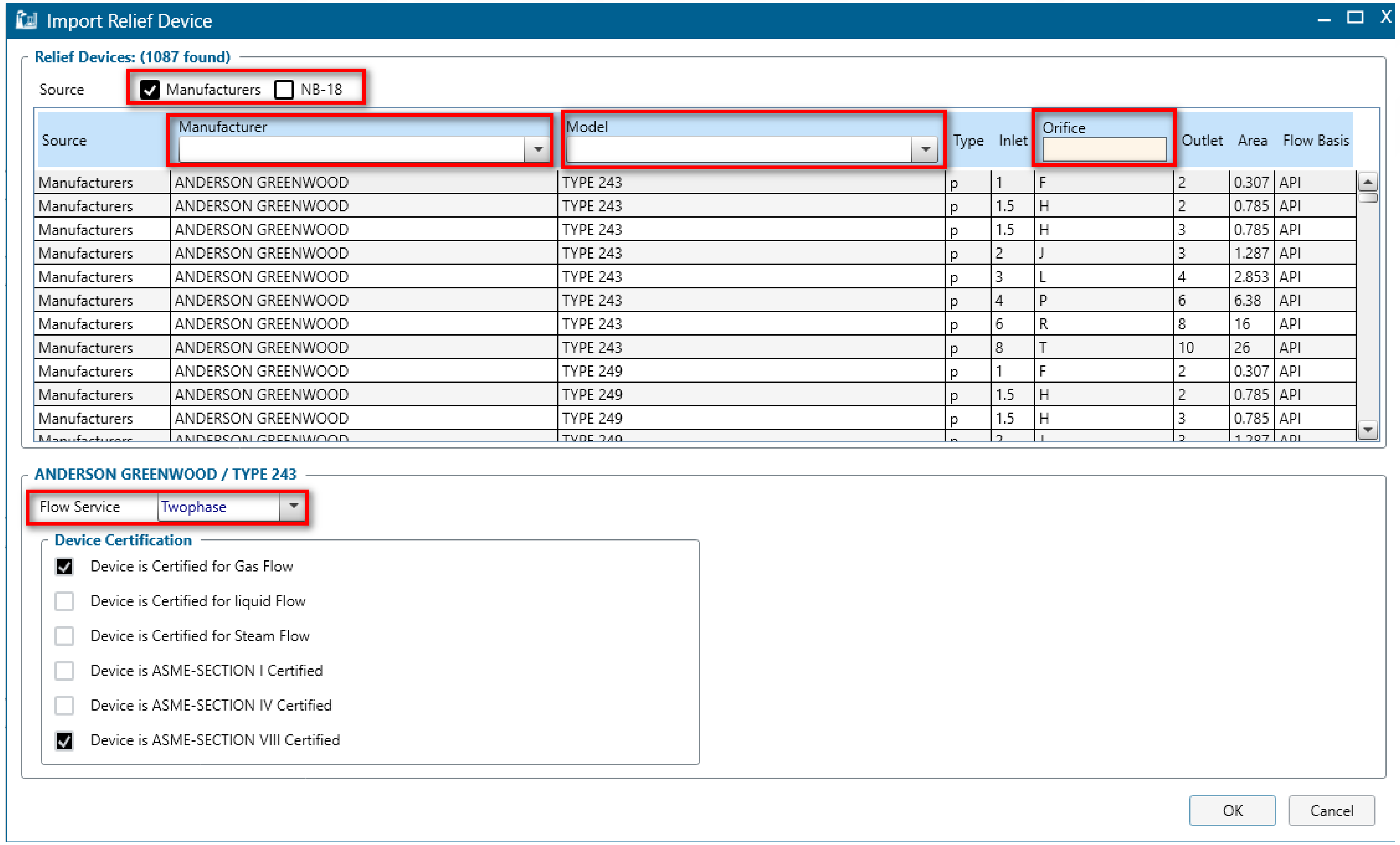
Always ensure the mixture Vapor-Liquid Equilibrium (VLE)



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Defining the piping layout and associated pressure relief device objects

- Click on “Settings” and a new window will pop up
- SuperChems™ contains a database with thousands of relief valves to select from
- You can filter by Source, Manufacturer, Model, Orifice, or Flow Service



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

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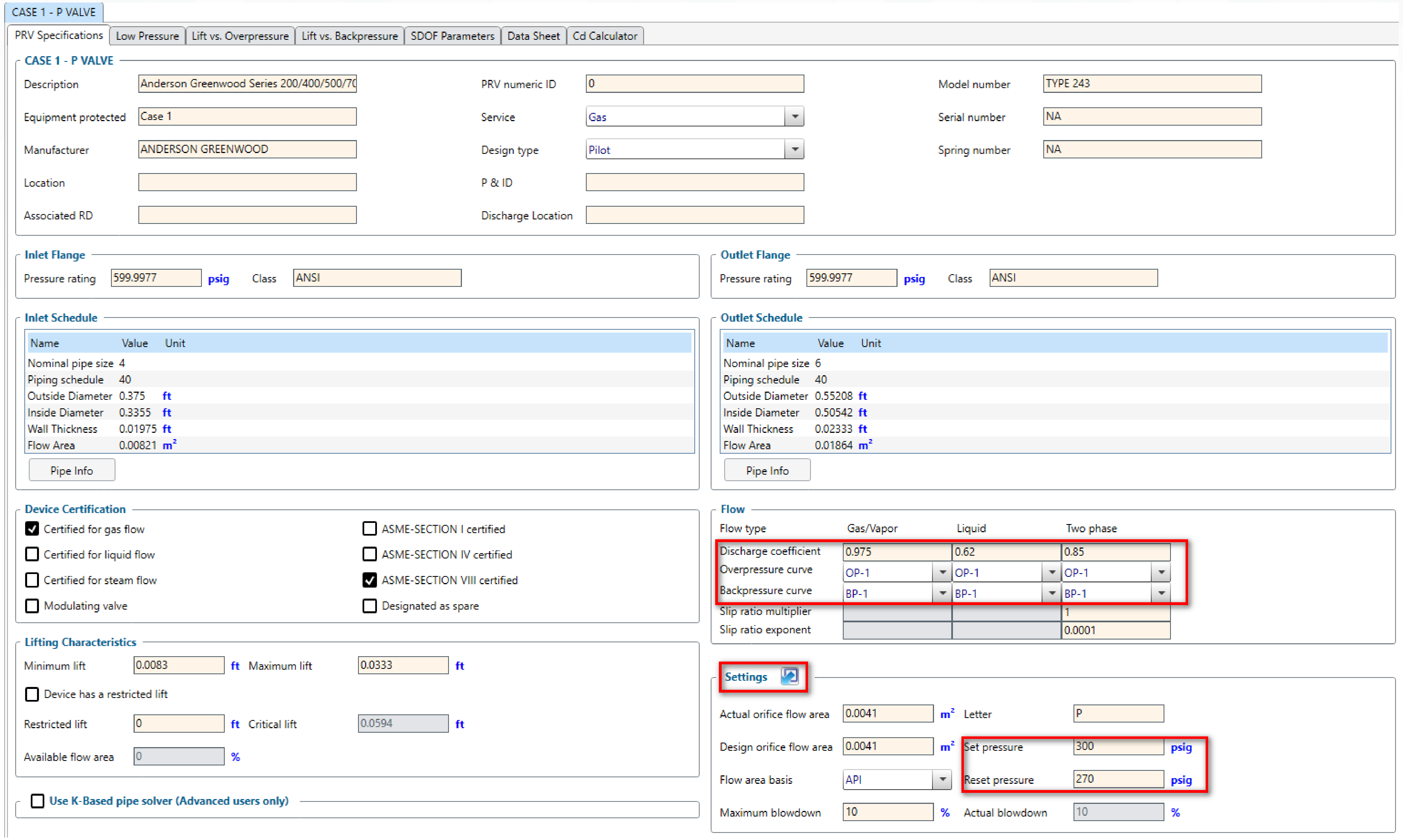
In this example, an Anderson Greenwood 4P6 pilot pressure relief valve is selected

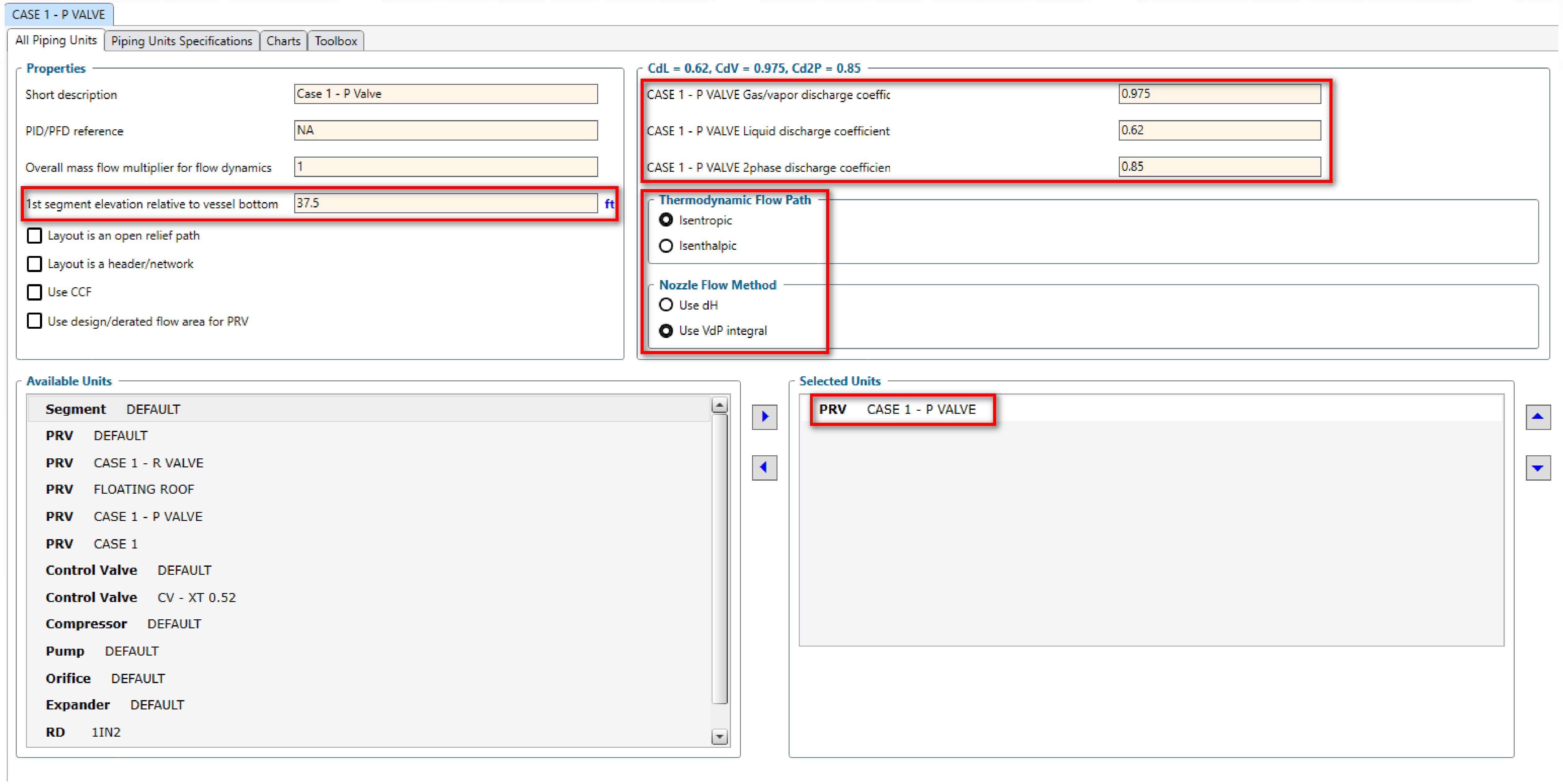
- SuperChems™ populates almost all required fields
- You still need to specify the Set Pressure and Reseat Pressure



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

In the Piping Layout object, select the applicable segments

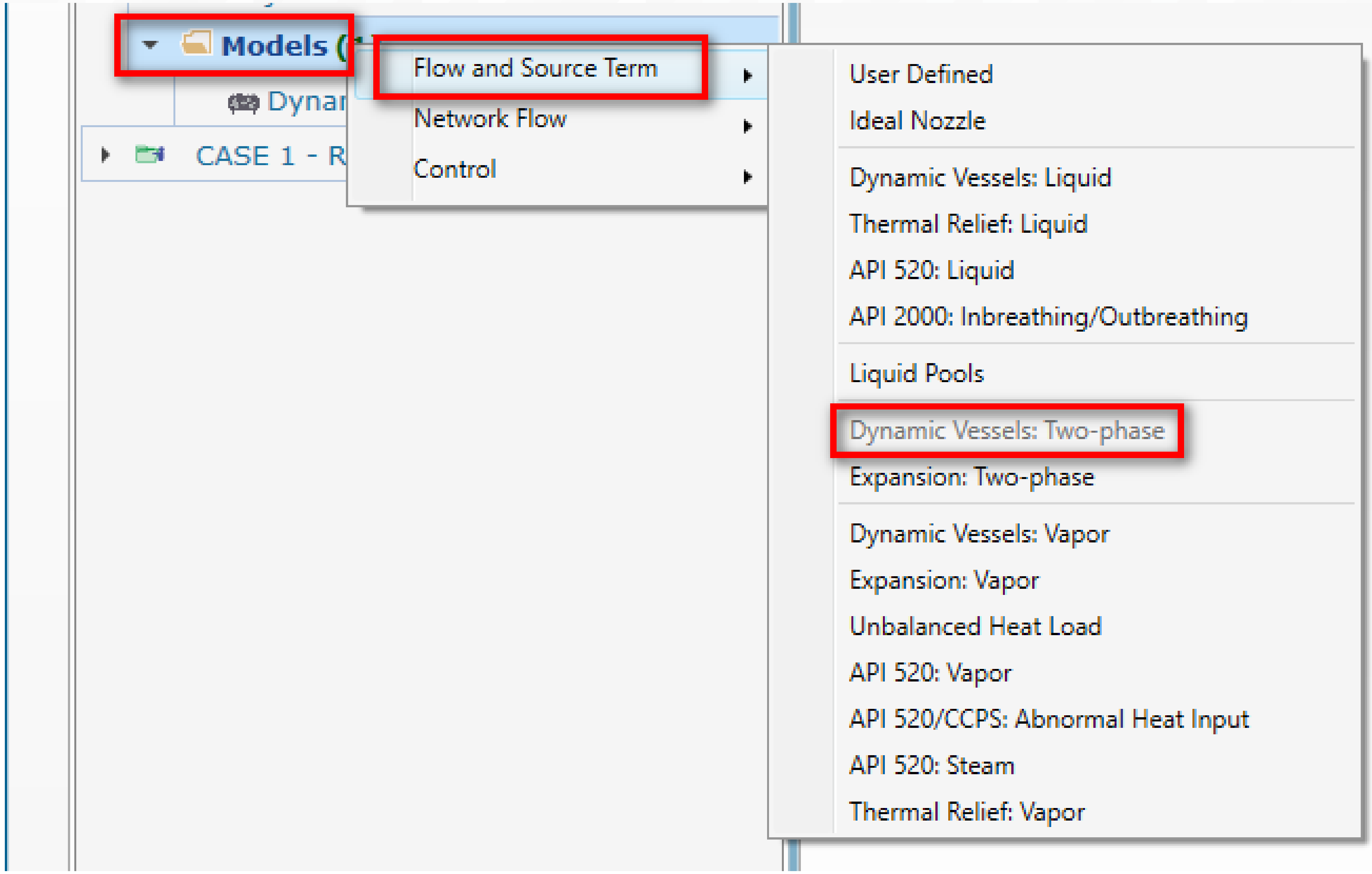
- Adjust the elevation of the "1st segment relative to vessel bottom"
  - Account for the length of top / bottom heads
- For this dynamic evaluation, we will only use the pilot 4P6 valve



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Next, identify and apply the correct source term model for the simulation

- Right click in “Models”
- Select “Flow and Source Term”
- Select “Dynamic Vessels: Two-phase”



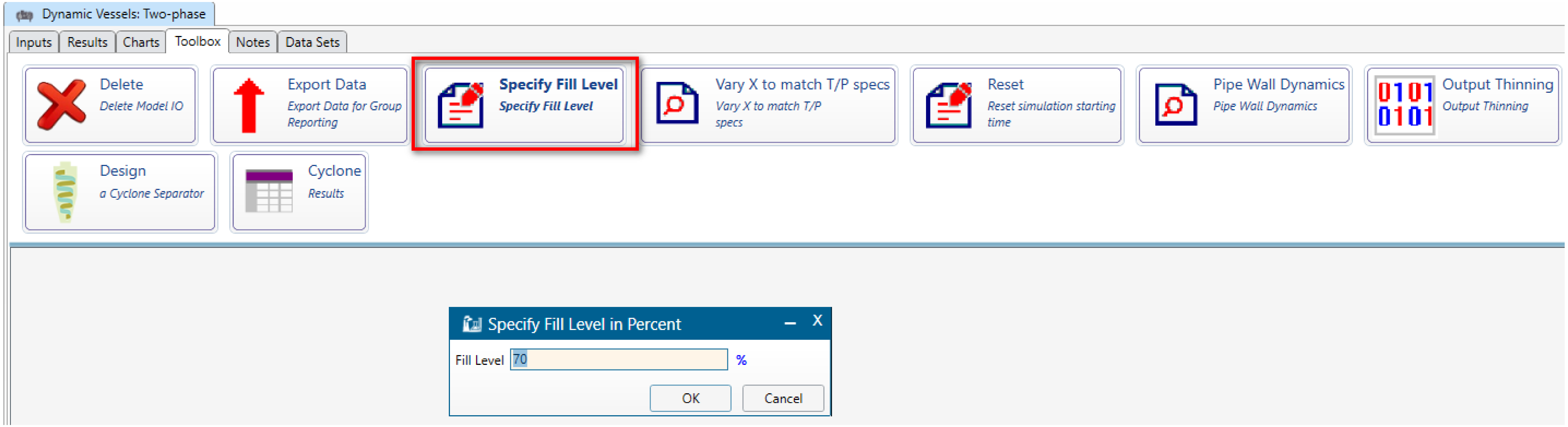
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

In the dynamic vessels two-phase model, specify initial conditions and simulation parameters

- Fluid Phase = Saturated Liquid
- Pressure = 200 psig
- Under relief piping path, specify the backpressure (0 psig) and Flow Type (Vapor)
- Starting Time = 0 hours
- Final time = 4 hours, fire duration
- Select "External fire exposure" checkbox
- Select "Perform Detailed Vessel Wall Heat Transfer Dynamics" checkbox and select the number of segments (5 in this example)

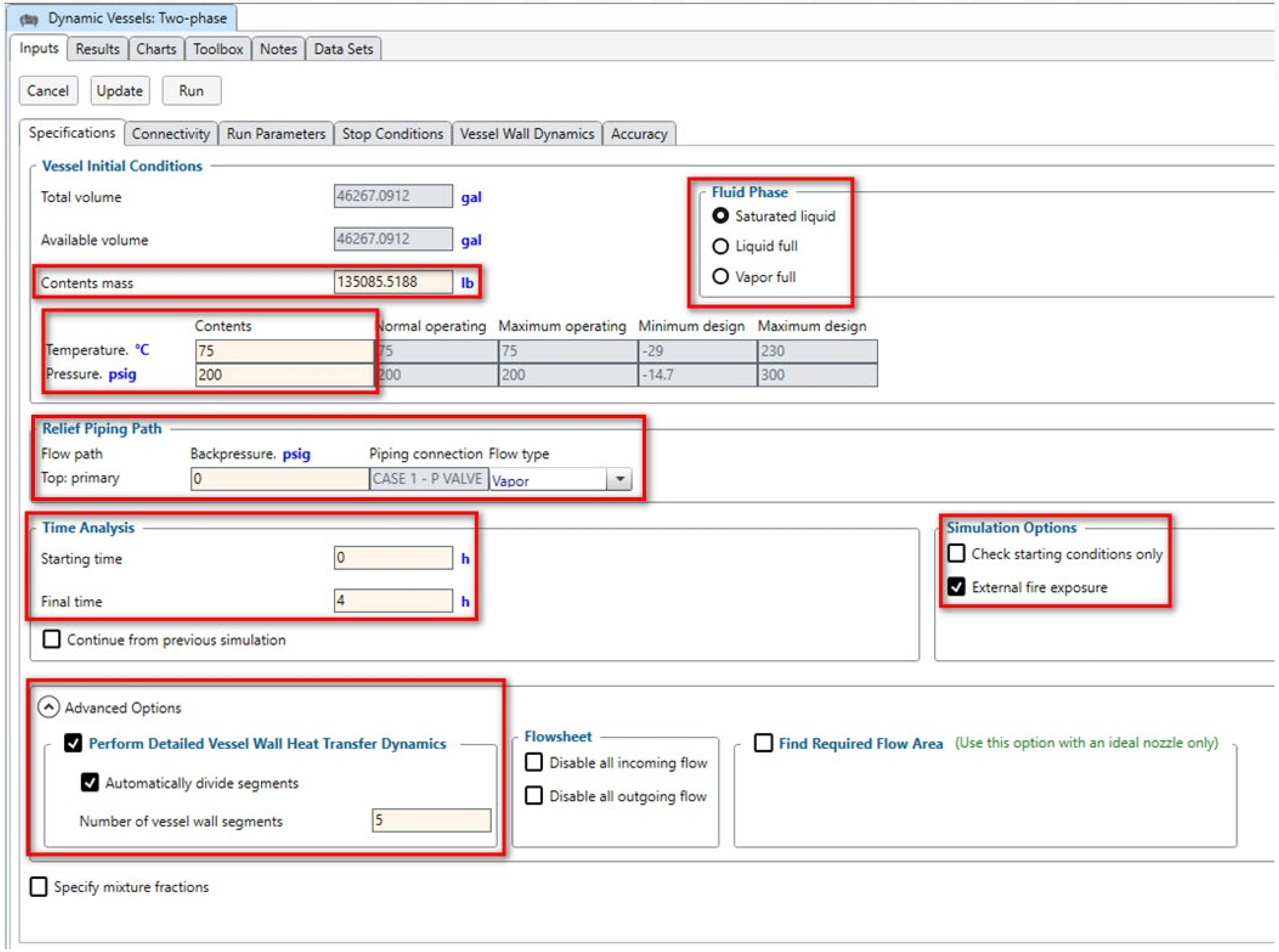
To properly calculate the mass contents, go to "Toolbox" and click "Specify Fill Level"

- In this example, the normal liquid level is 70%
- Based on the initial pressure and mixture composition, SuperChems™ will calculate the initial mass and starting temperature



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

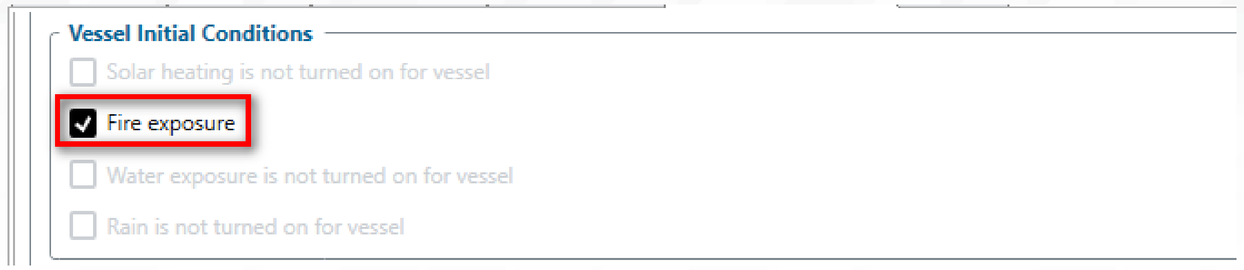
The screenshot below shows the initial conditions and parameters for the dynamic simulation



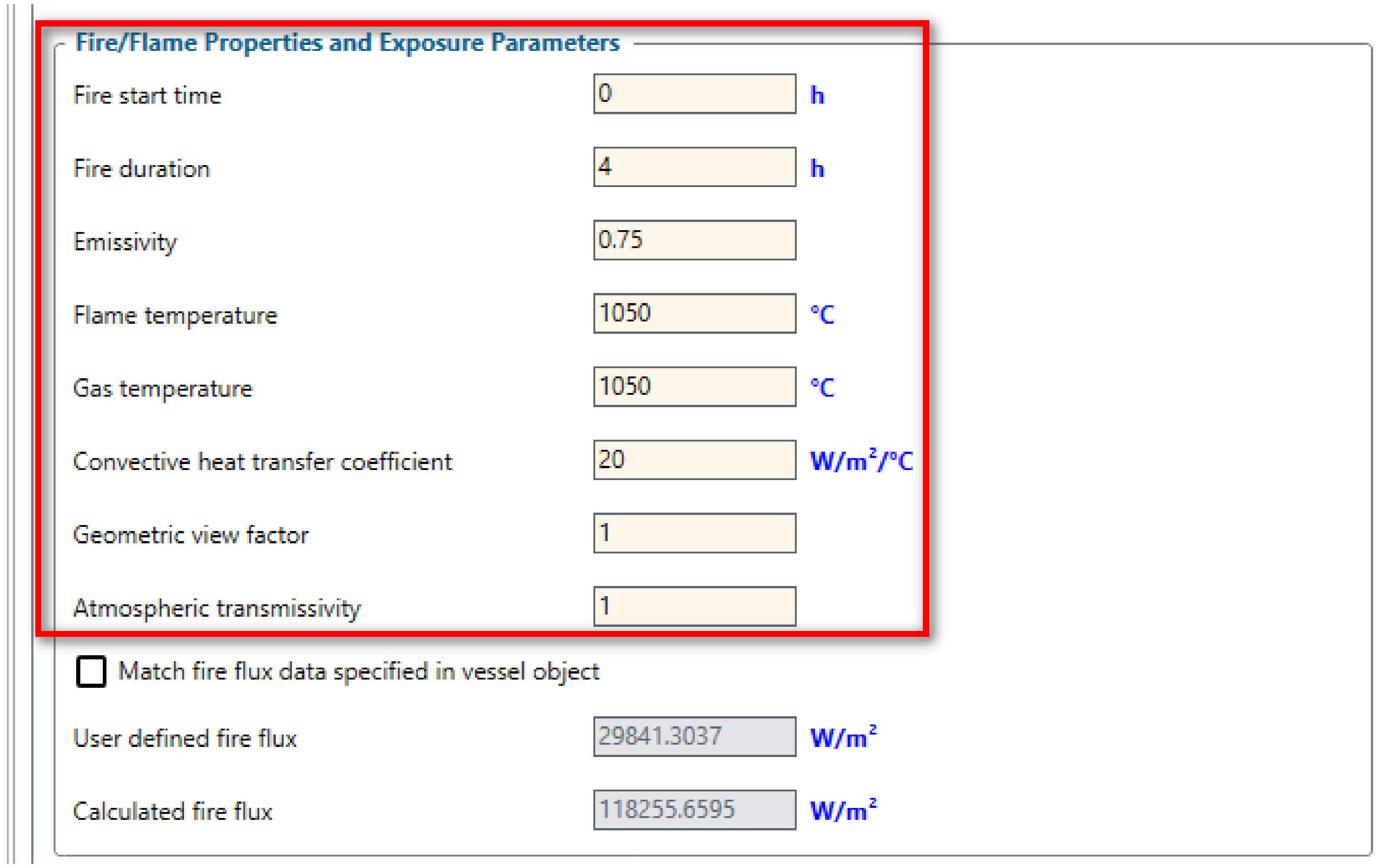
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

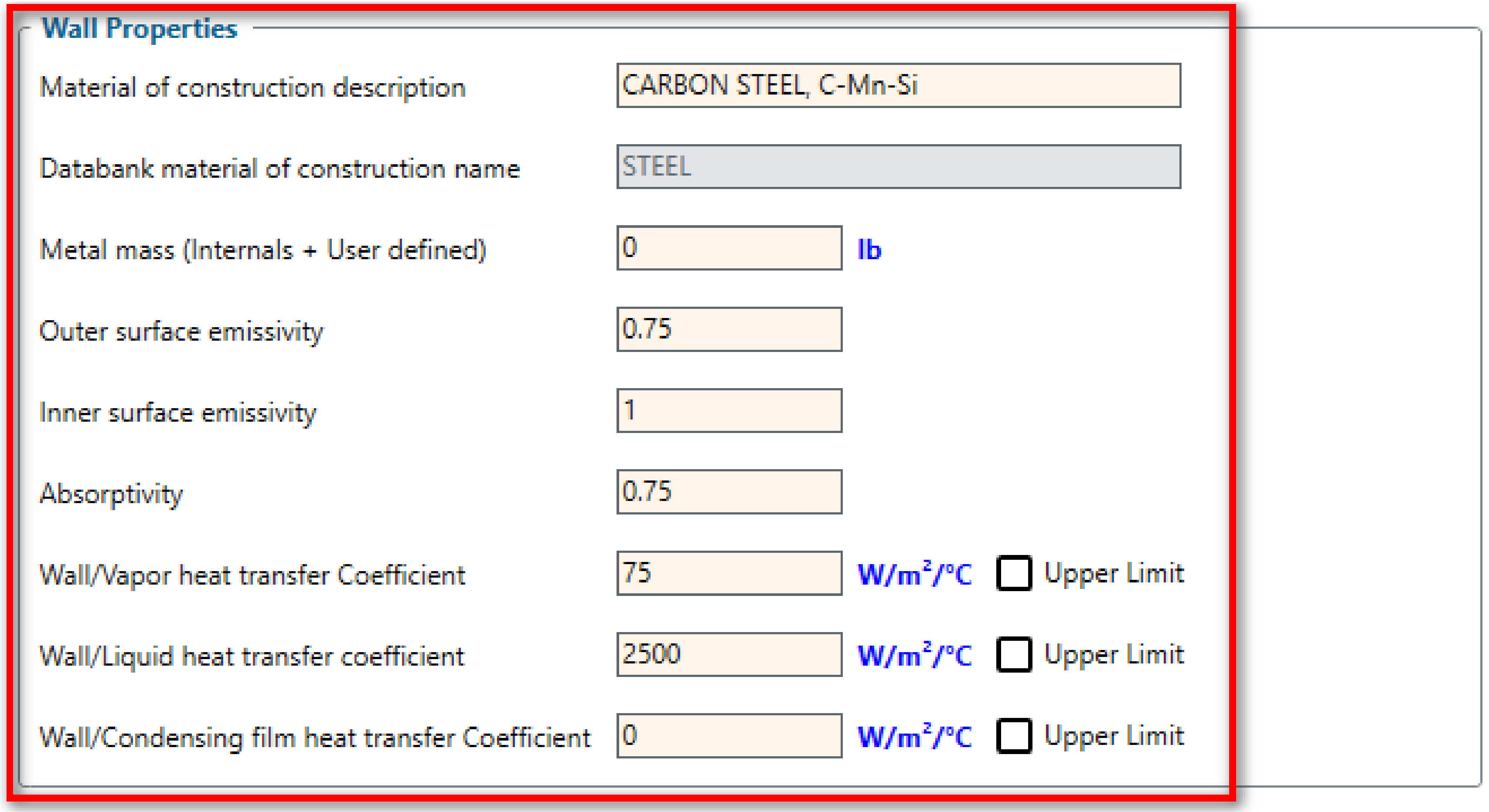
Specify the vessel wall dynamics properties to use the fundamental heat transfer equation outlined in API Std 521

- Ensure that the “Fire Exposure” option is checked



- Input the correct parameters based on API Standard 521 7th edition for the “Fire/Flame Properties” and the “Wall Properties” sections

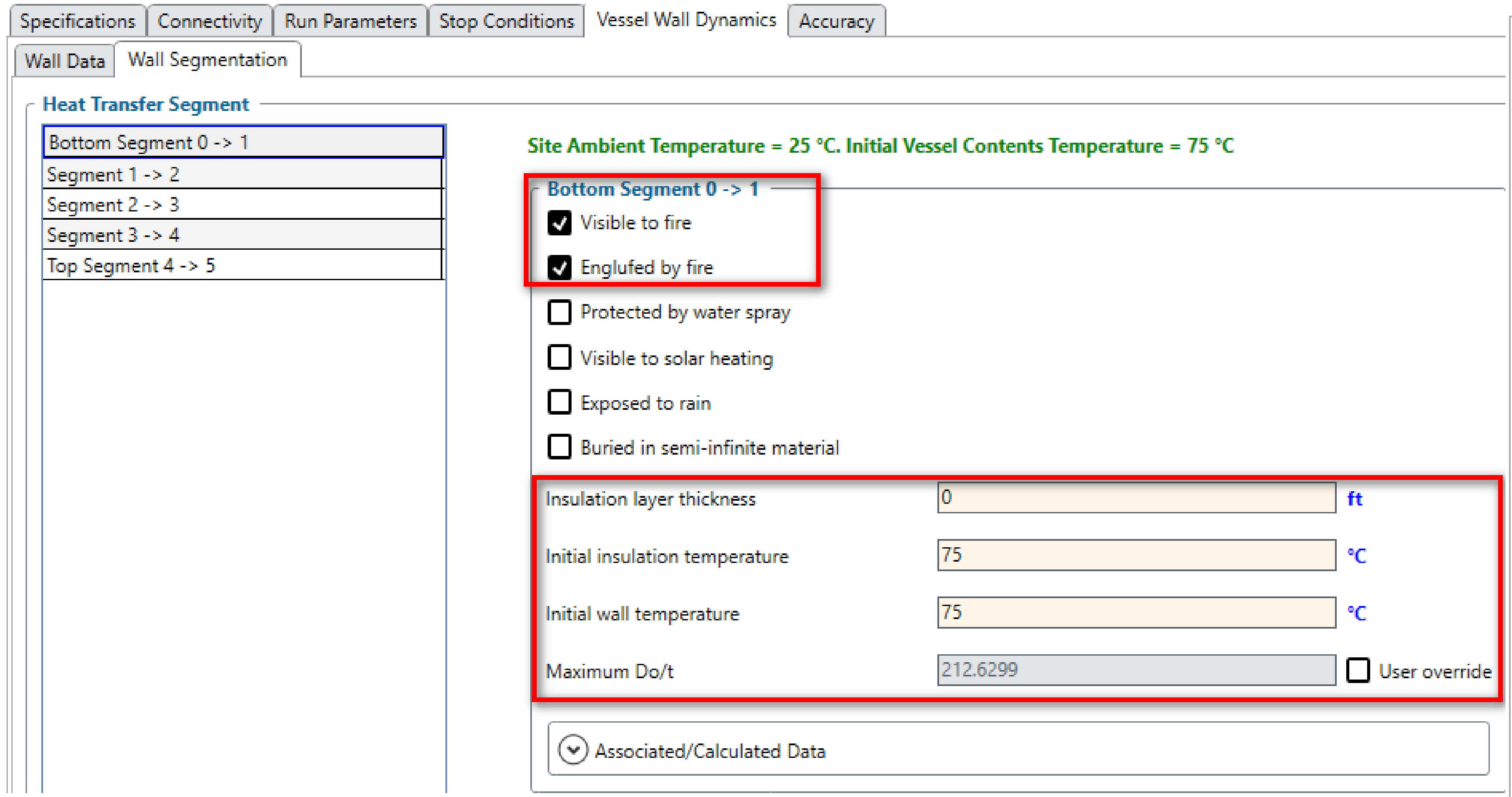


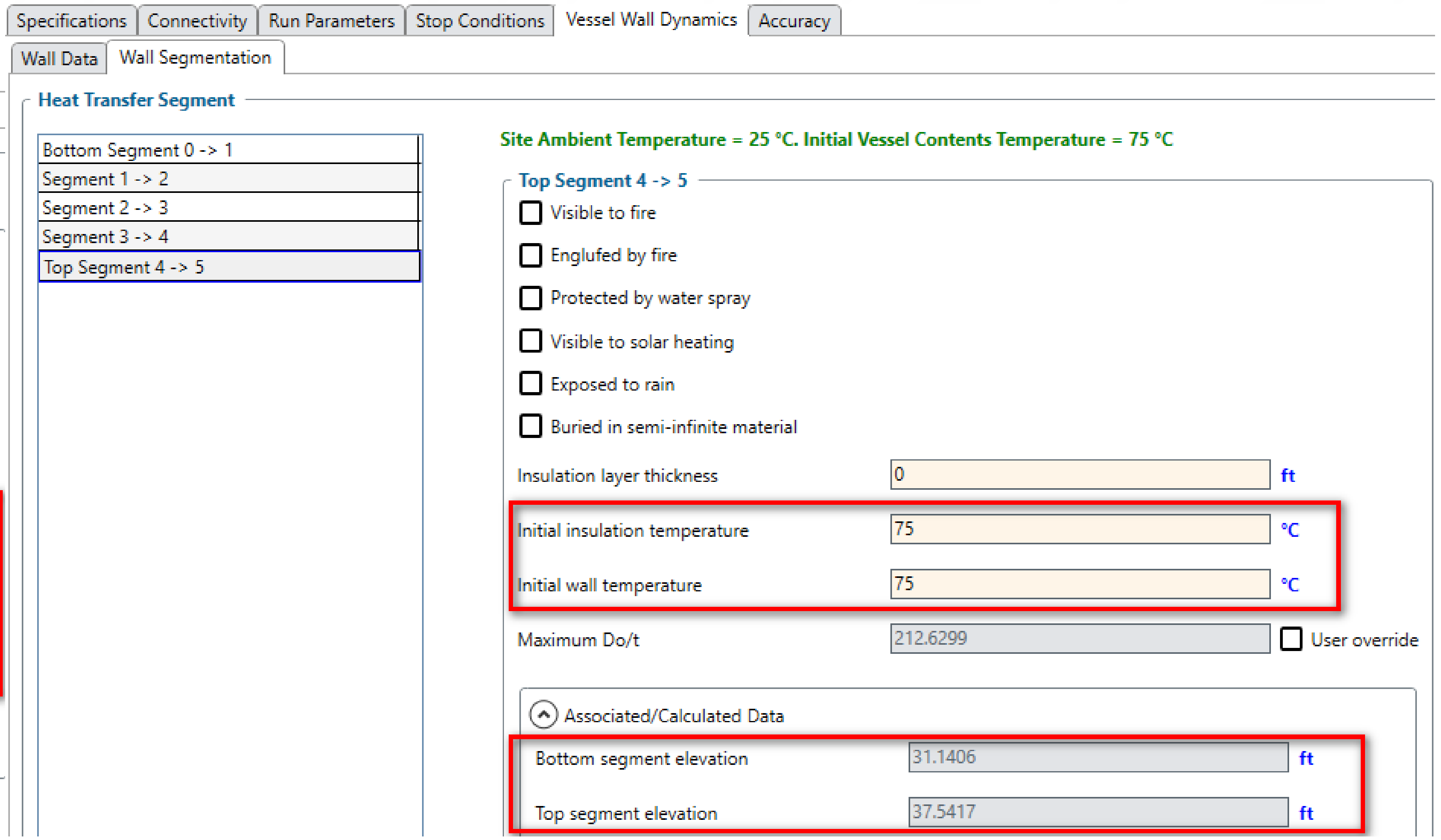


Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Define the properties for all the wall segments

- Specify wall temperature equal to fluid starting temperature (75 °C) and check the applicable "Visible to fire" and "Englufed by fire" checkboxes for all segments as applicable





Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Click “Run” and wait for the dynamic simulation to finish

Dynamic Vessels: Two-phase

Inputs | Results | Charts | Toolbox | Notes | Data Sets

Summary | *Flows* | *Profiles* | *Detailed Profiles* | *Composition*

Export

Vessel Options & Considerations

External fire exposure

Relief Piping

Vessel Connection	Relief Piping	Backpressure psig	Flow type
TOP: Primary Piping	CASE 1 - P VALVE	0	Vapor

Overall Balance

		Initial	Final	Final - Initial
Time	h	0.0000	4.000	4.000
Temperature	°C	74.892	947.7	872.8
Pressure	psig	200.0	271.3	71.327
Vapor mass	lb	3,353	4,921	1,568
Vapor volume	gal	13,895	48,337	34,442
Liquid mass	lb	1.31732E+05	0.0000	-1.31732E+05
Liquid volume	gal	32,372	0.0000	-32,372
Total mass	lb	1.35086E+05	4,921	-1.30164E+05
Total volume	gal	46,267	48,337	2,070
Volume Full of Liquid	%	69.968	0.0000	-69.968

Design Boundaries

		Maximum	Time h	Point	
Pressure	psig	414.1	0.5020	173	1.38 x DESIGN P
dP/dt	psig/h	1,904	0.0760	34	
Temperature	°C	947.7	4.000	716	3.90 x DESIGN T
dT/dt	°C/h	2,108	0.6200	287	
Impulse	lbf	3,163	0.5020	171	
Fire heating input	W	1.60372E+07	0.0000	0	

Composition Balance

		Initial Liquid	Final Liquid	Initial Vapor	Final Vapor	Initial Total	Final Total	Change Total
ETHANE	lb	6,225	0.0000	763.5	79.491	6,989	79.491	-6,909
PROPANE	lb	19,478	0.0000	1,019	430.8	20,497	430.8	-20,066
n-BUTANE	lb	39,635	0.0000	890.9	1,343	40,526	1,343	-39,183
n-PENTANE	lb	66,394	0.0000	680.1	3,068	67,074	3,068	-64,006
Totals		1.31732E+05	0.0000	3,353	4,921	1.35086E+05	4,921	-1.30164E+05

Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

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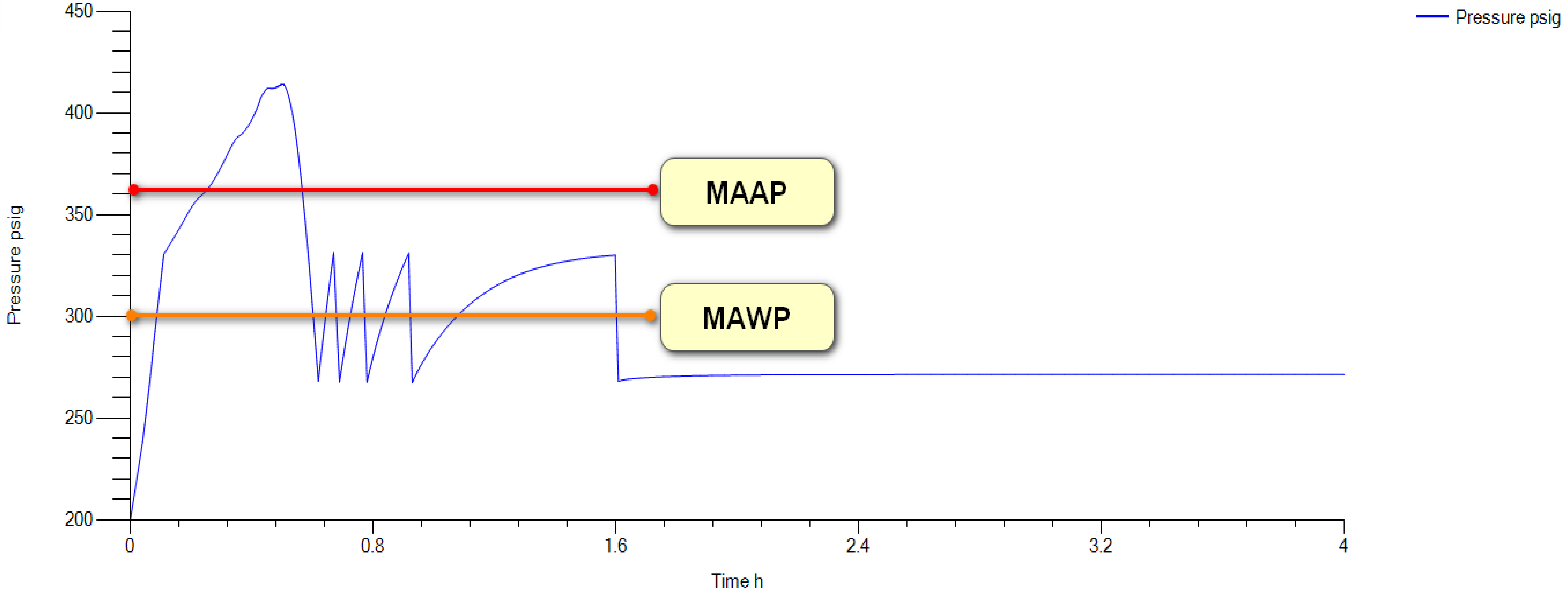
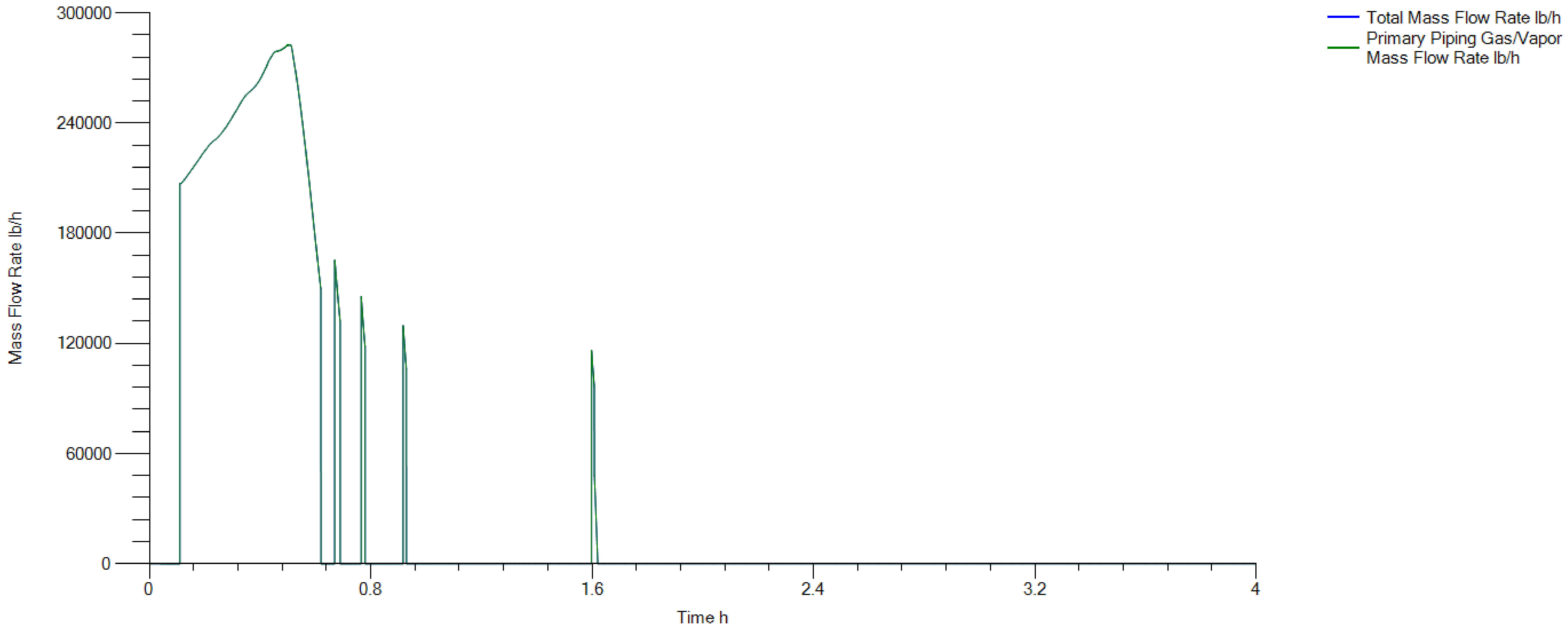
Under “Charts” tab, the user can illustrate several types of dynamic results such as pressure profile



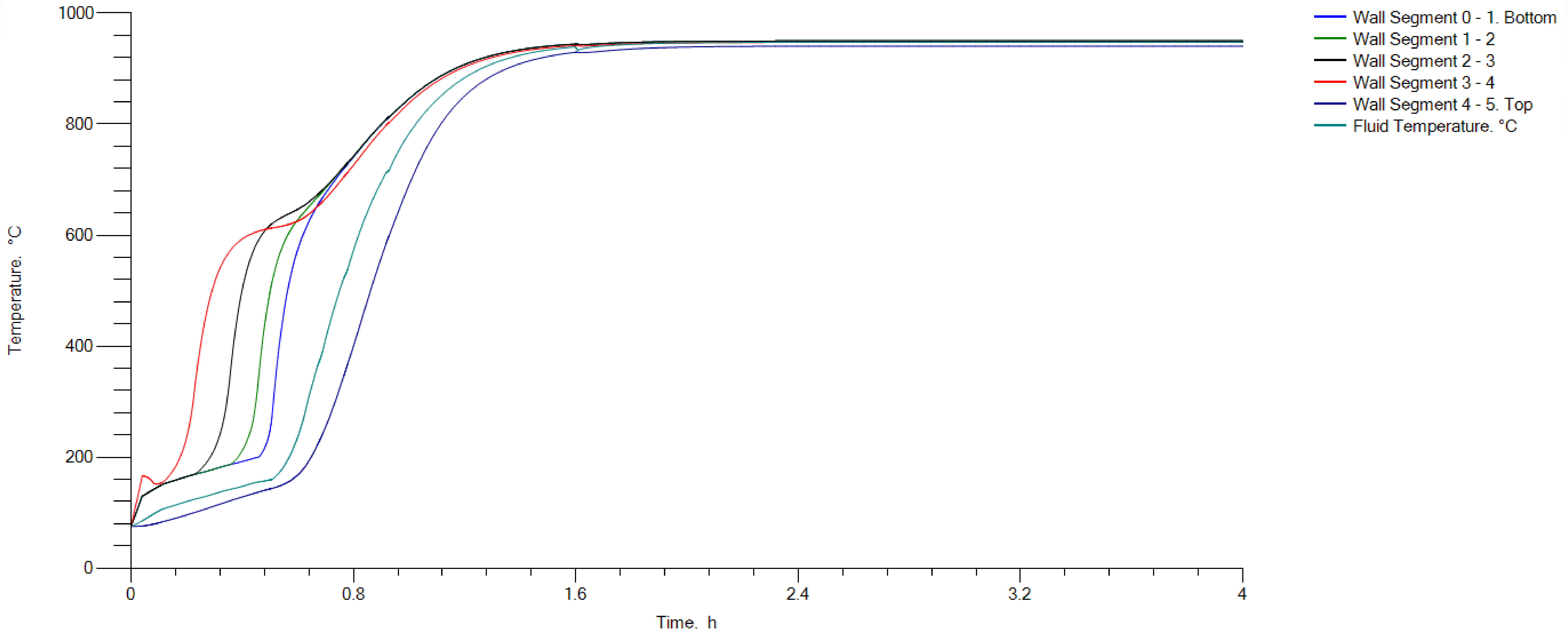
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

The user can also illustrate other results such as venting history profile



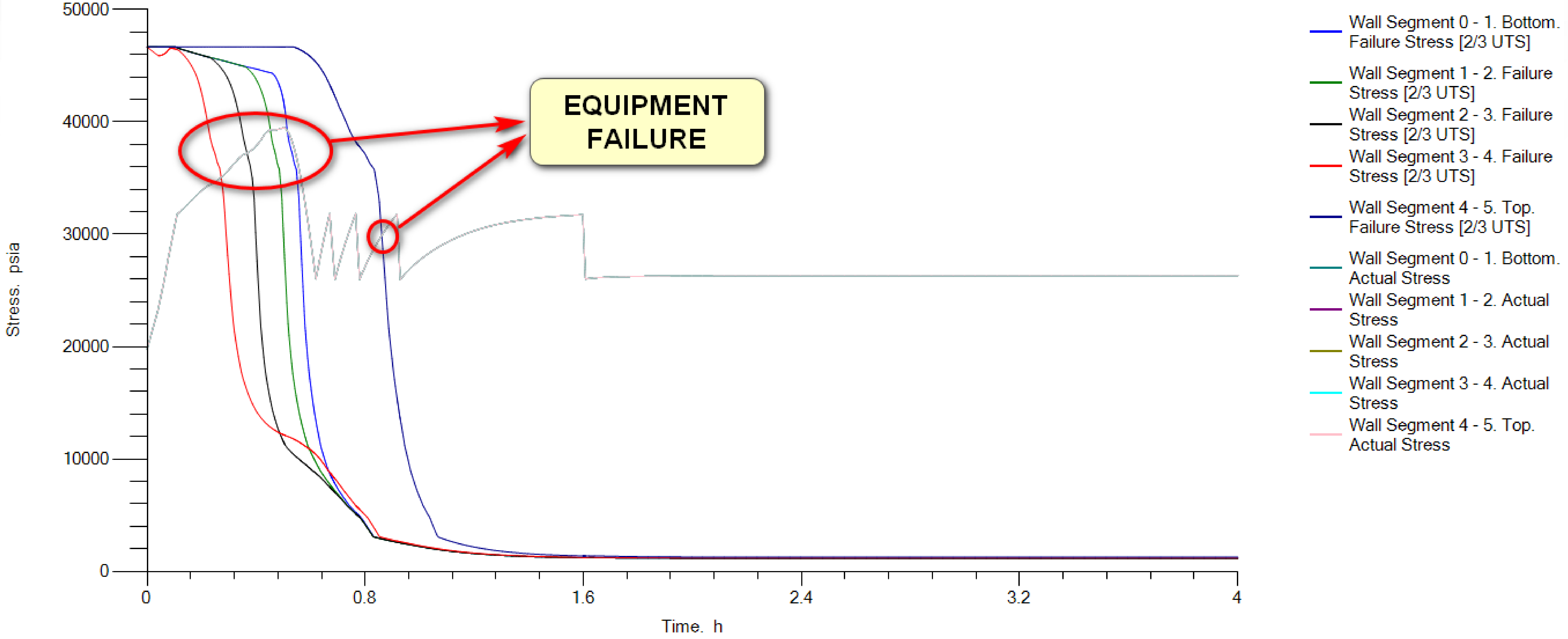
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Under “Wall Dynamics” tab, the user can illustrate wall segment temperature profiles



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Based on the wall failure stress profiles, V-100 stress exceeds 2/3 of the Ultimate Tensile Strength (UTS)

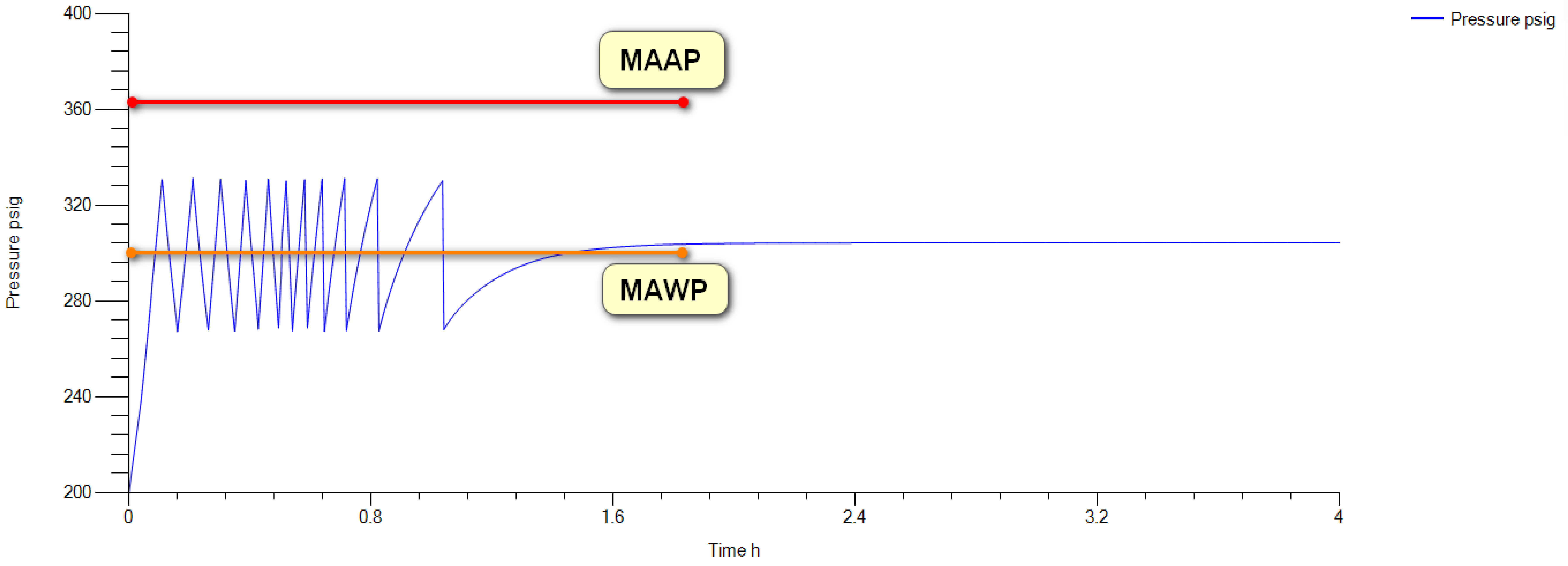


Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

PRV-100 may not adequately protect V-100 in the event of exposure to an open pool fire

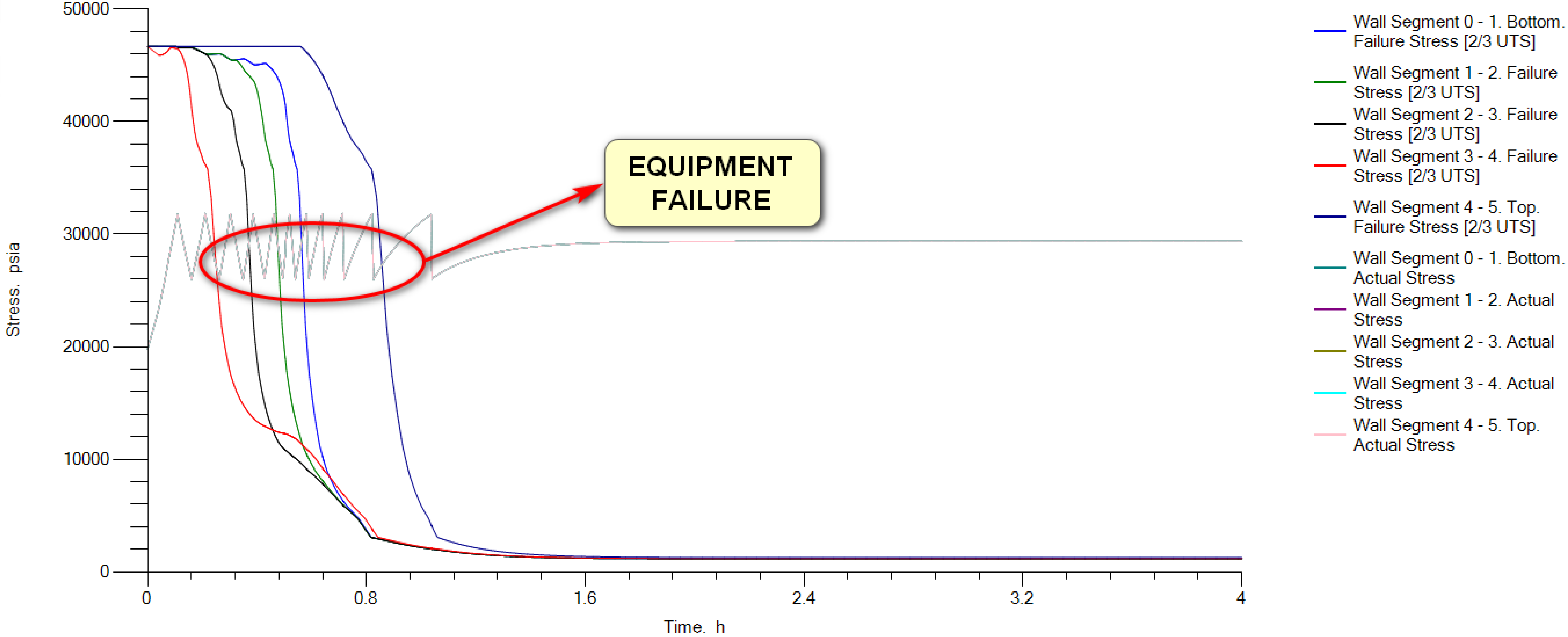
- The pressure relief system may be inadequate because the expected vessel pressure is above the Maximum Allowable Accumulated Pressure (MAAP = 1.21 x MAWP)
- Additionally, the vessel stress exceeded 2/3 of the UTS, so the equipment is expected to fail before 4 hours
- Next, we investigate the impact of installing a larger relief device (6R8)
- Note that valid mitigation solutions are typically the following:
  - Install fire-proof insulation
  - Replace the pressure relief valve for an emergency depressuring system
  - Use of water sprays

From the overpressure point of view, the system seems adequate because maximum pressure is below MAAP (1.21 x MAWP)



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

However, V-100 is still expected to fail after 15 minutes of fire exposure because the vessel stress exceeds 2/3 of the UTS



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Case Studies in SuperChems™
Case 2 – Low-Pressure Atmospheric Tank

Atmospheric Storage Tank T-100 has been identified to be exposed to thermal radiation due to a nearby pool fire

- A nearby loss of containment scenario results in leakage of a flammable material resulting in a pool fire
- Using SuperChems™, it is estimated that T-100 is exposed to a heat flux of 25 kW/m^2 with a duration of 5 minutes
- The properties of the vessel under analysis are illustrated to the right

Floating Roof

T-100

MAWP < 15 psig
MAWT = 250 °C
Length = 35 ft
Diameter = 100 ft
Bottom Head = Flat
Top Head = Floating Roaf
Shell Thickness = 0.5 in
Thickness of Top/Bottom Heads = 0.5 in
Material = SA 516-70
Pressure = 0 psig
Temperature = 25 °C
Liquid Level = 85%
Molar Composition = 100% Decane

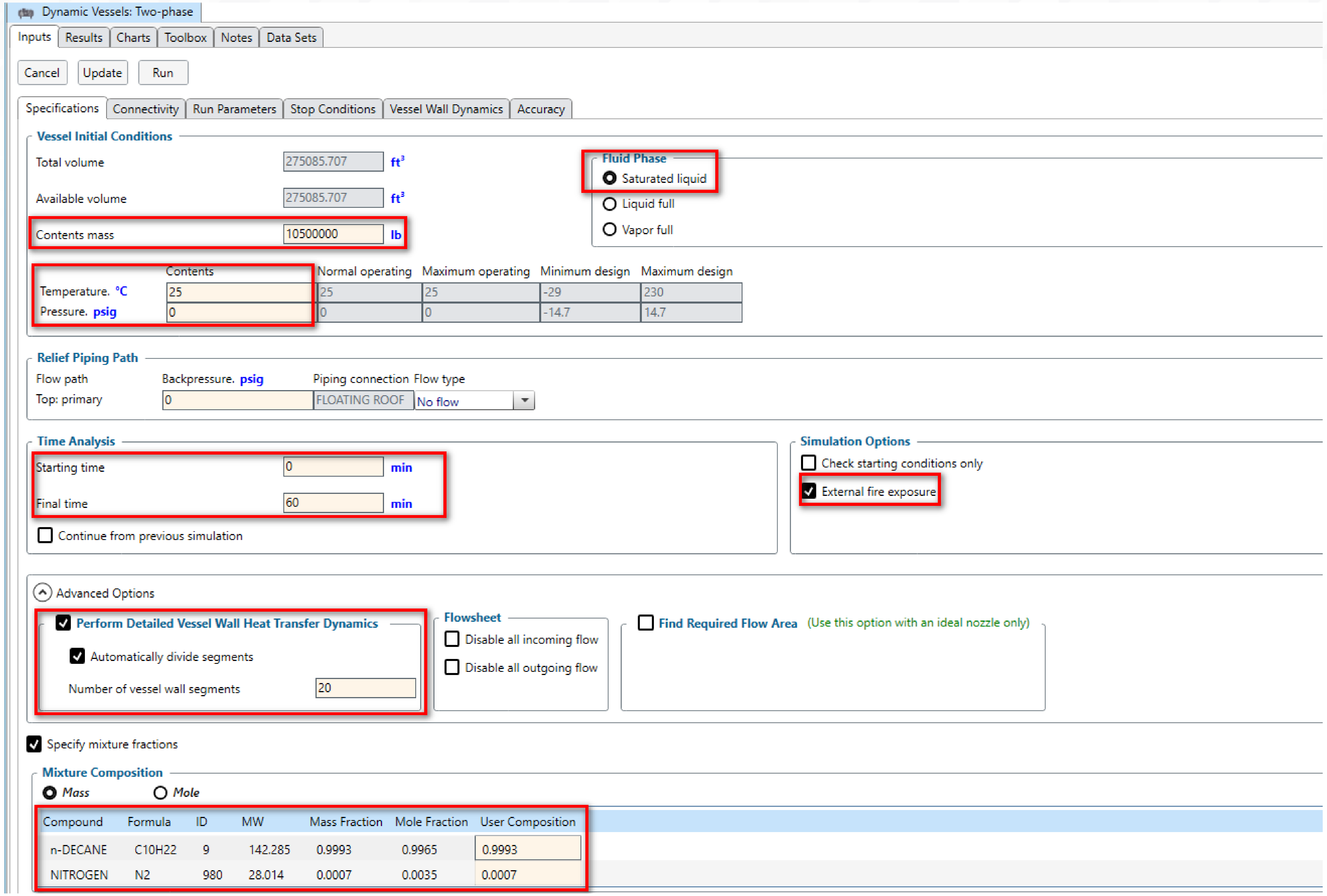
Source: ioMosaic Corporation

API Standard 650 may be used to define the failure criterion for low-pressure atmospheric storage tanks

- The goal is to identify whether the mechanical integrity of the tank would be compromised, resulting in potential equipment failure
- Evaluation of T-100 mechanical integrity needs to account for the tank wall temperatures and heat radiation received
- Based on API Standard 650 12th Edition, the failure temperature of a carbon steel storage tank is indicated as 93 °C, and for well-maintained and inspected storage tanks, the failure temperature is indicated as 250 °C

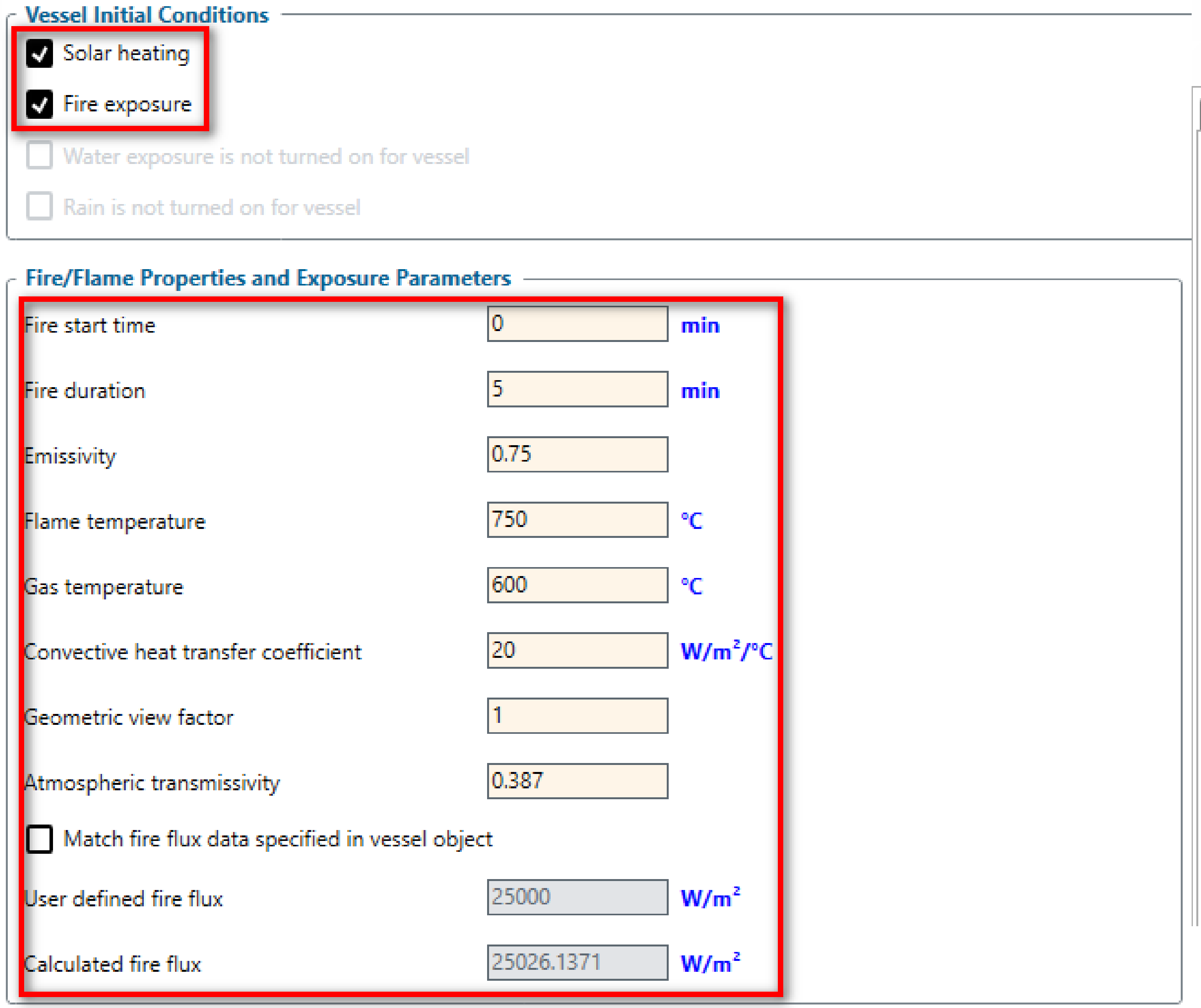
Source: API Standard 650, 2013, "Welded Tanks for Oil Storage", 12th Edition

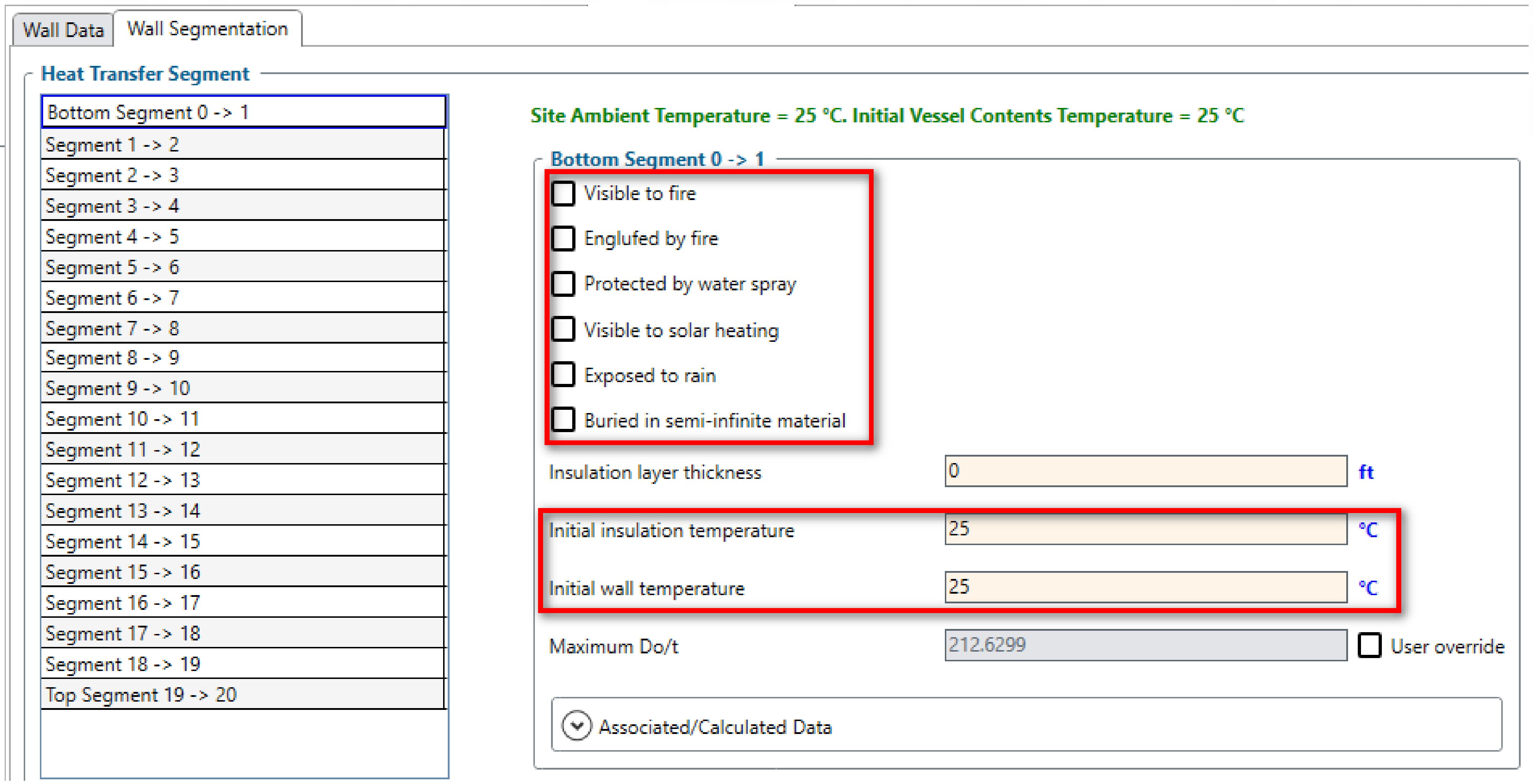
The image below illustrates simulation initial conditions and parameters when tank T-100 is exposed to 25 kW/m^2



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

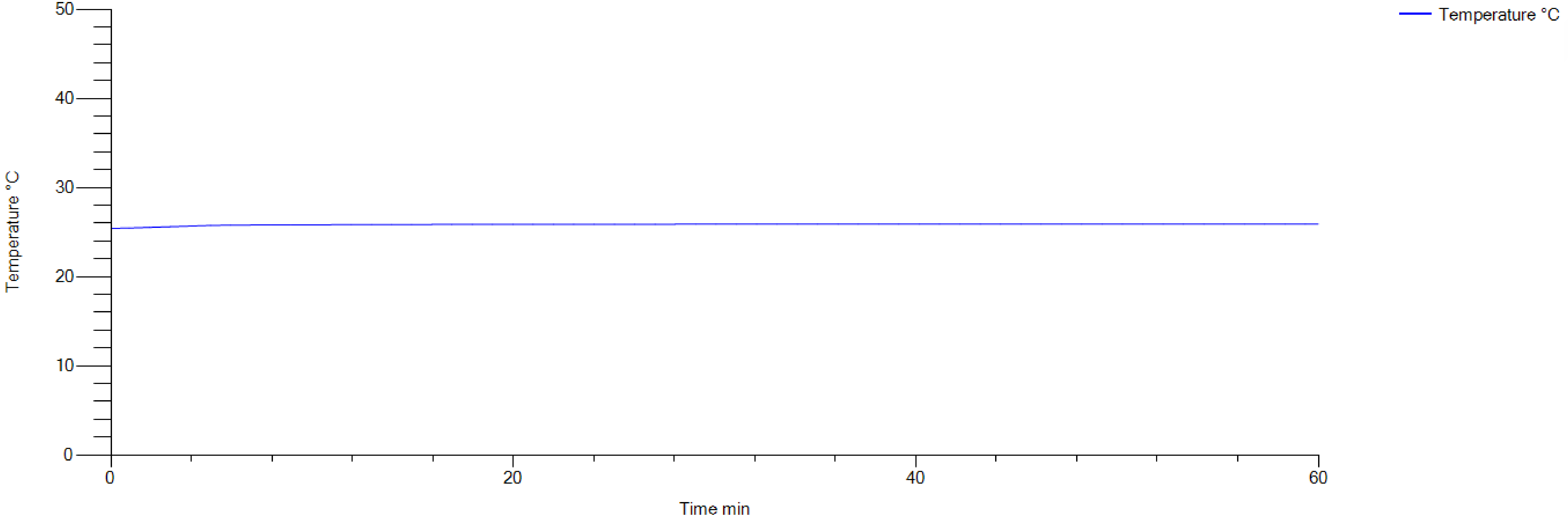
Wall dynamics parameters and properties are properly specified for this scenario





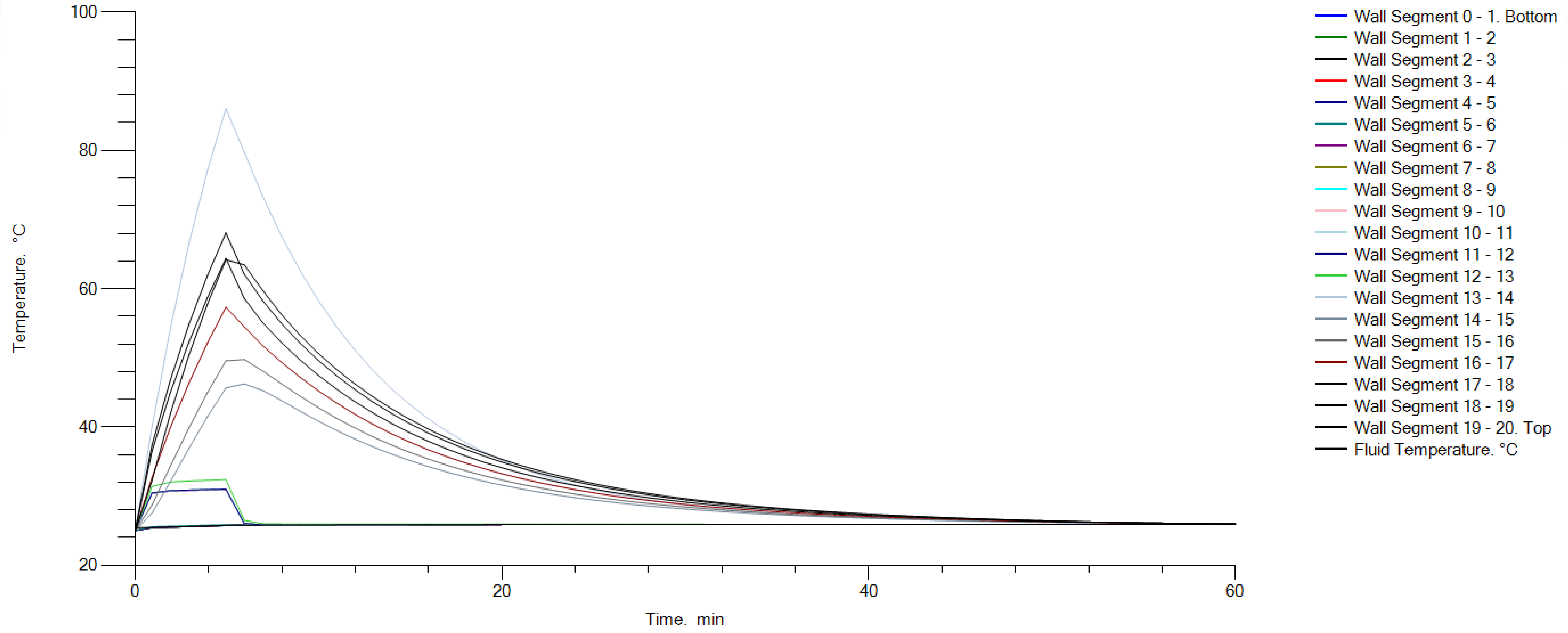
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Based on the dynamic simulations results, it can be observed that T-100 fluid temperature stays reasonably constant



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Wall temperature profiles indicate that segments not covered by liquid get hotter sooner and then cool down after 5 minutes



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

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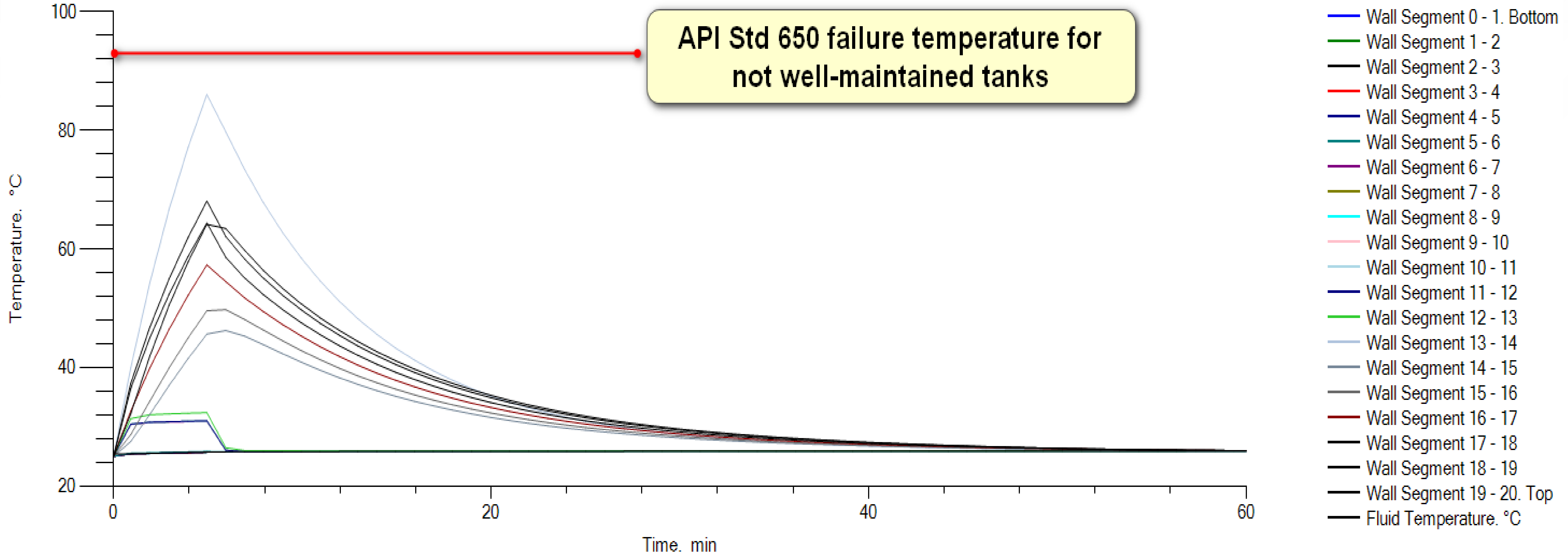
T-100 mechanical integrity is not expected to be compromised based on the detailed wall dynamics results



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Wall Dynamics Tutorial Summary

The following topics have been addressed during today's presentation

- Evaluation of vessel and piping wall temperatures using the fundamental heat transfer equation outlined in API Standard 521
- Advantages and characteristics of the wall segmentation approach implemented in SuperChems™
- Application of the wall dynamics approach in SuperChems™ via 2 case studies: (1) evaluation of a pressure vessel, and (2) evaluation of a low-pressure atmospheric tank

Thank you very much!
Questions?

About ioMosaic Corporation

Through innovation and dedication to continual improvement, ioMosaic has become a leading provider of integrated process safety and risk management solutions. ioMosaic has expertise in a wide variety of areas, including pressure relief systems design, process safety management, expert litigation support, laboratory services, training, and software development.

ioMosaic offers integrated process safety and risk management services to help you manage and reduce episodic risk. Because when safety, efficiency, and compliance are improved, you can sleep better at night. Our extensive expertise allows us the flexibility, resources, and capabilities to determine what you need to reduce and manage episodic risk, maintain compliance, and prevent injuries and catastrophic incidents.

Our mission is to help you protect your people, plant, stakeholder value, and our planet.

For more information on ioMosaic, please visit: **www.ioMosaic.com**