LNG SAFETY RESEARCH ON FIRE AND CRYOGENIC SPILL PROTECTION

PFPNET HOUSTON ONE-DAY TECHNICAL EVENT

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Disclaimer

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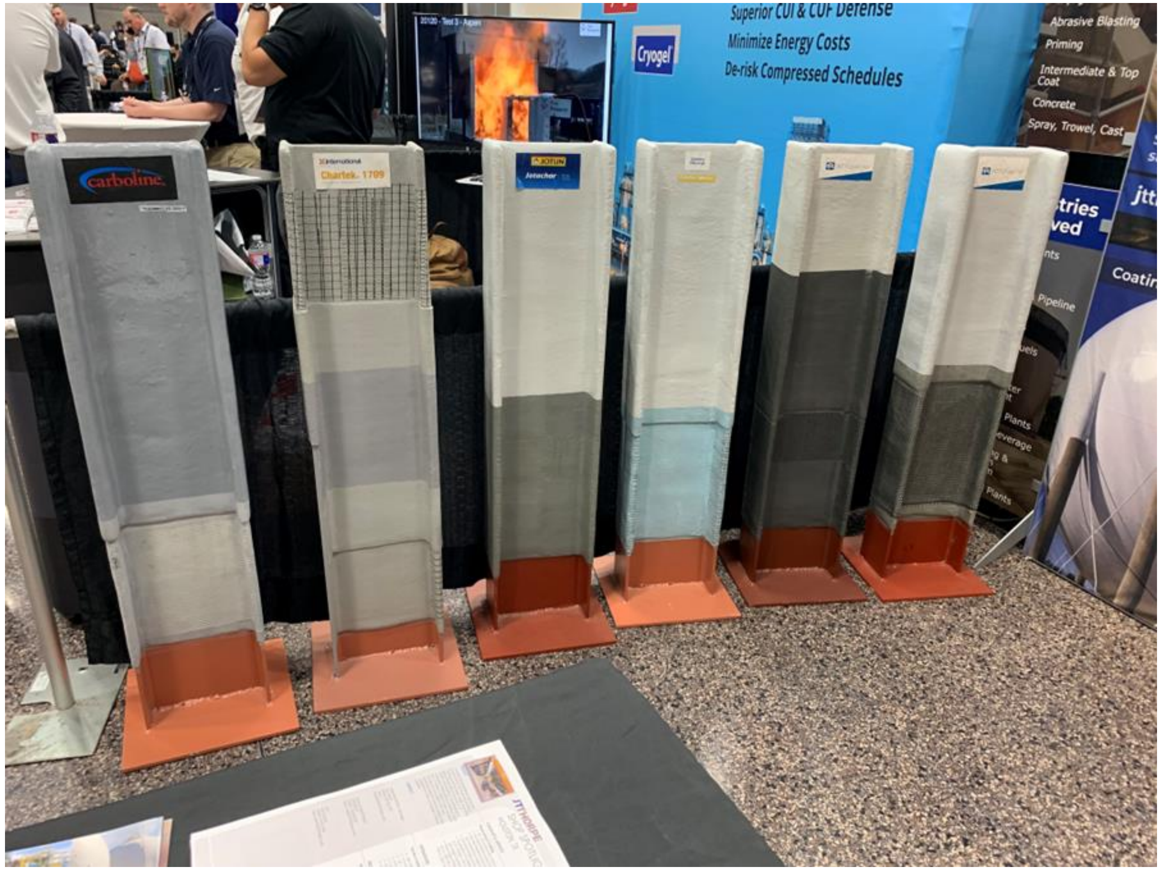
Outline

- Research Objective
- Methodology
- Development of Fire and Cryogenic Release Scenarios
- Fire and Cryogenic Release Response Assessment
  - Equipment
  - Steel Structures
- PFP and CSP Systems – Assessment Methodologies
- Recommendations



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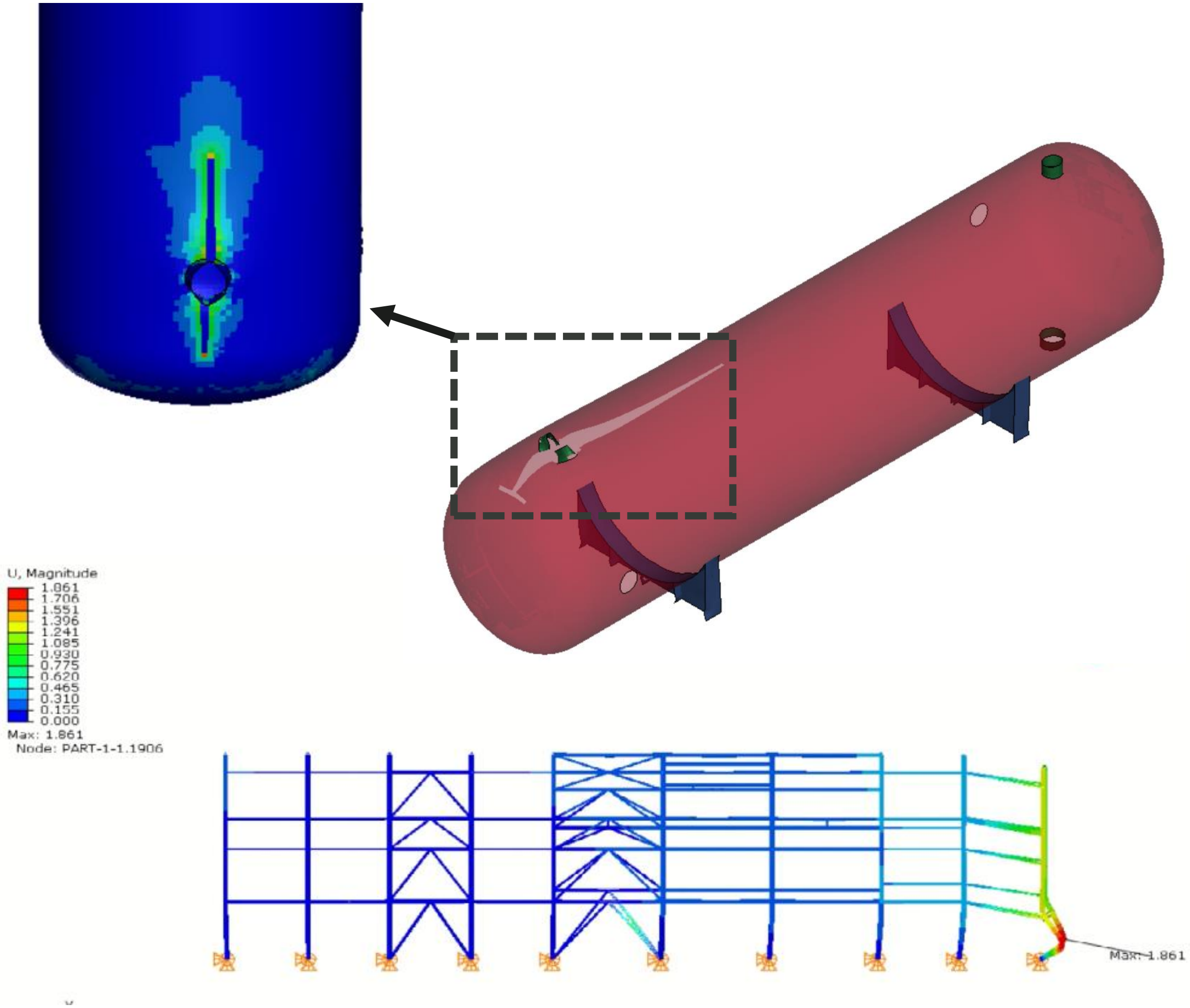
Research Objective

- The objective of this research is to develop methodologies and criteria for selecting, applying, and maintaining cryogenic and fireproofing systems designed to limit the extent of cryogenic and fire-related consequences at LNG facilities.
- We reviewed, investigated, and analyzed response, failure mechanisms, and thresholds for equipment, piping and structures for fire and cryogenic release scenarios. We also reviewed and analyzed passive fire and cryogenic spill protection systems.



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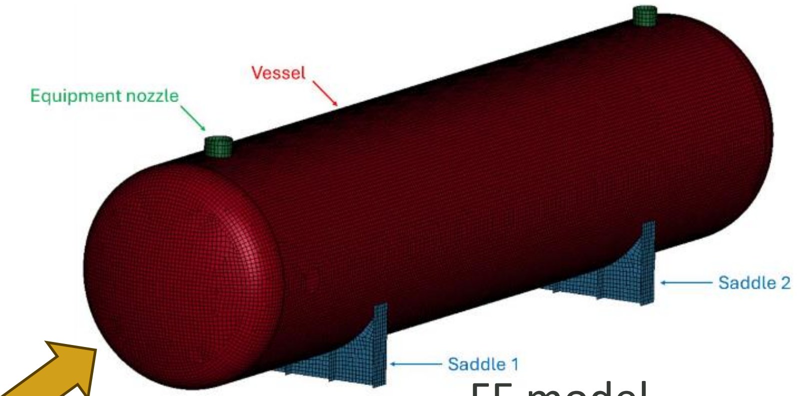
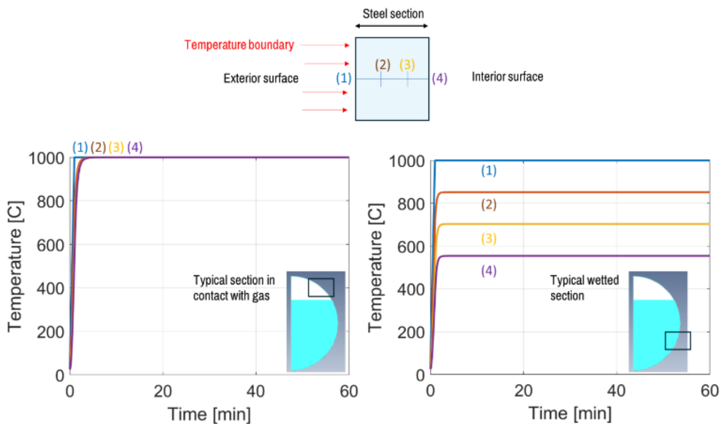
Fire Response Assessment Methodology

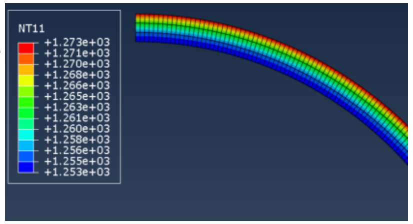


FE model

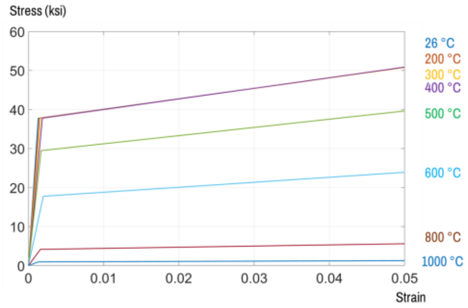
Heat transfer analysis



Temperature mapping

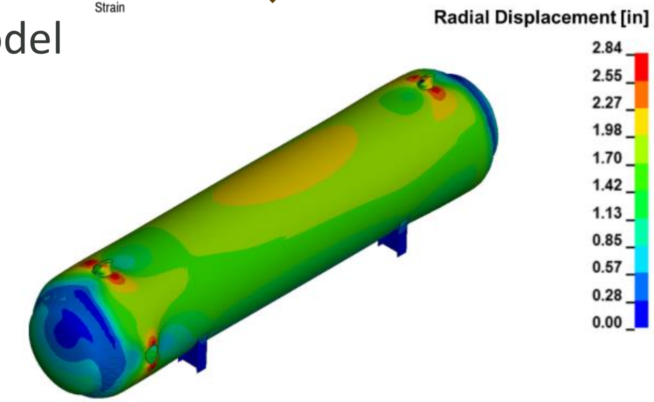


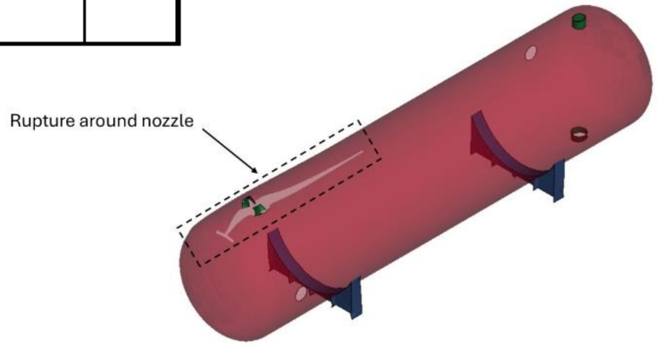
Scenario	Fire Type	Flame Length / Background Radiation Extent at 37.5 kW/m² (meters)			Duration (min.)		
		0.12 in. Hole	0.75 in. Hole	2 in. Hole	0.12 in. Hole	0.75 in. Hole	2 in. Hole
Gas release from feed gas into the plant	Jet	2 / 2.5	11 / 13	28 / 32	60+	60+	60+
Gas release from booster compression into processing	Jet	3 / 4	20 / 23.5	34 / 39	60+	4	2
Liquid (LNG) release from cold box processes	Spray	8 / 9	43 / 49.6	113 / 138	60+	5	3
Gas or liquid release from heavy hydrocarbons in liquefaction processes	Spray	6 / 7	28 / 32.3	70 / 85.5	60+	10	4



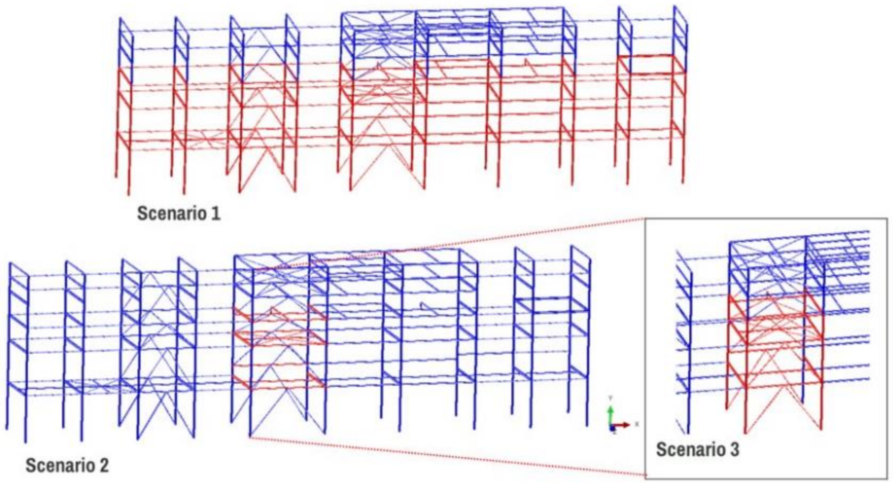
Material model

Nonlinear stress analysis

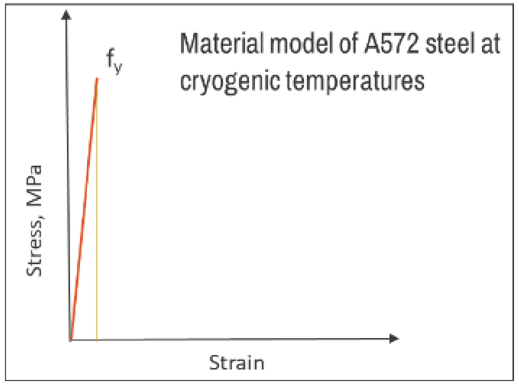




Cryogenic Release Response Assessment Methodology



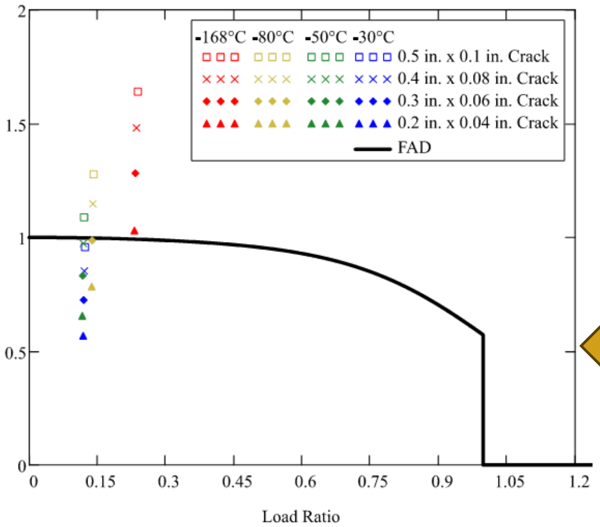
FE model with cryo scenarios

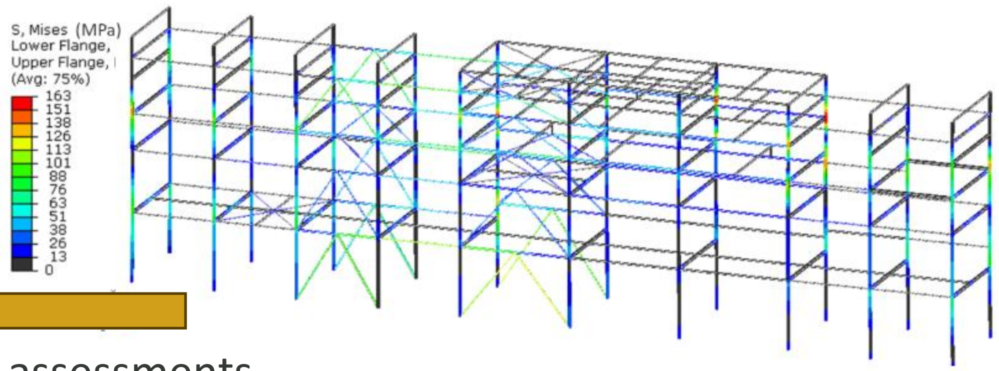


Material model

Stress analysis

Hole Size (in.)	System Pressure (barg)	Extent / Effective Width (m)		
		1% Liquid Content	At -80°C	At -30°C
2	5	21.4 / 3.7	43.6 / 17.3	79.9 / 60.7
	10	20.2 / 2.5	44.7 / 13.5	82.7 / 50.4
	15	20.4 / 2.2	45.8 / 12.1	88.0 / 48.1
	25	20.5 / 1.9	45.7 / 9.9	90.9 / 40.5
	35	21.1 / 1.8	44.9 / 8.4	92.0 / 35.7
	45	21.3 / 1.8	46.0 / 8.1	94.4 / 33.7
4	5	34.2 / 6.6	70.5 / 30.3	127.0 / 100.4
	10	43.5 / 8.1	91.5 / 39.8	163.4 / 129.0
	15	44.7 / 7.4	94.1 / 34.8	169.2 / 119.5
	25	43.9 / 5.9	97.1 / 29.4	176.3 / 104.8
	35	44.5 / 5.4	98.7 / 26.4	183.1 / 97.2
	45	44.3 / 5.0	99.8 / 24.3	187.6 / 90.4





FFS assessments

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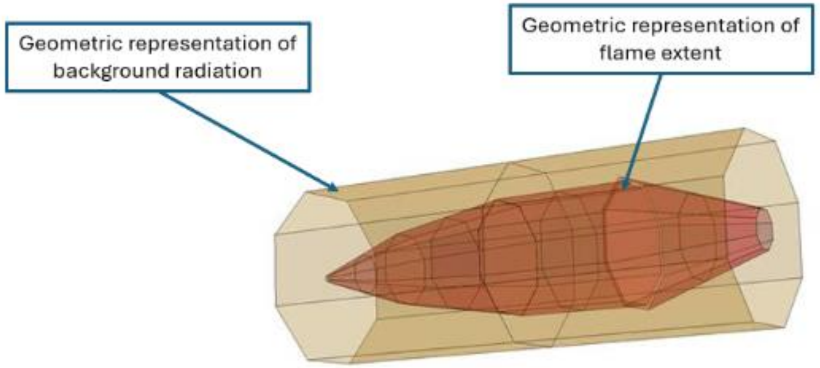
Case Studies

- The case studies examine pool fires, jet fires, cryogenic pools, and cryogenic sprays
- Fires consider a minimum characterization of the primary flame, background radiation, and event duration
- The application of these extents (with respect to PFP specification development) can be done in several ways:
  - Numerous discrete flames – with varying directions
  - A cumulative impact area (vol) – more conservative approach
  - Frequency/exceedance impacts – less conservative approach
- The characterization of cryogenic scenarios treated in a similar manner as fires, defining a primary exposure and background condition
  - Background impacts – cryogenic embrittlement thresholds can vary more significantly than those for fires



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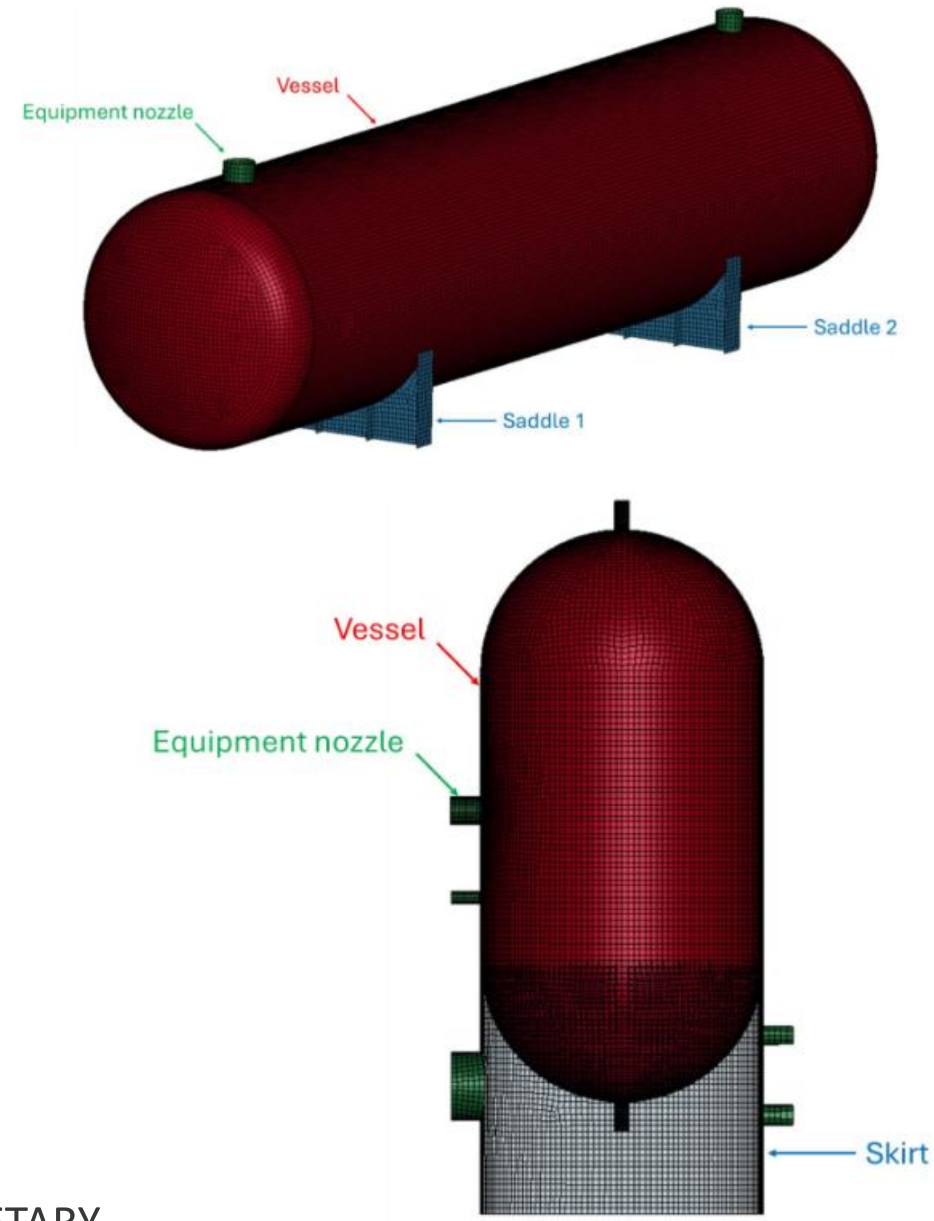
Equipment / Pressure Vessels

- Propane bullet vessel
  - 107 ft long and 24 ft dia. horizontal vessel made of ASME SA516 Grade 70 carbon steel
  - Thickness of 1'' for vessel and 0.5'' for saddle and nozzles
- Vertical pressure vessel
  - 33 ft long and 17 ft dia. vessel made of ASTM SA240 304L stainless steel
  - Thickness of 6.69'' for vessel and skirt, 1'' for nozzles
- Analysis cases include variations in the fill level, operating internal pressure, and depressurization.
- Unprotected and protected (by cementitious PFP) cases considered
- Loads: gravity, internal pressure, thermal loads



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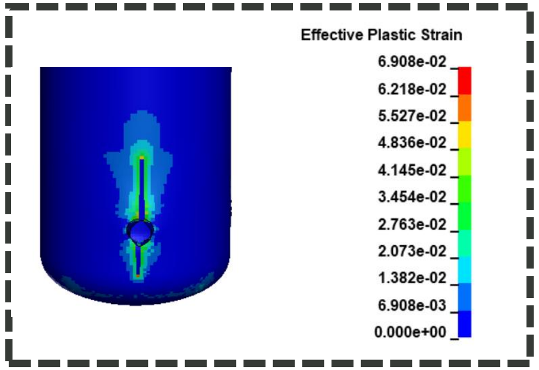
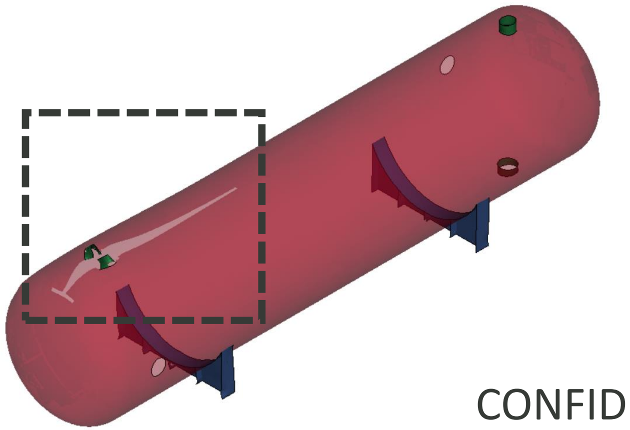
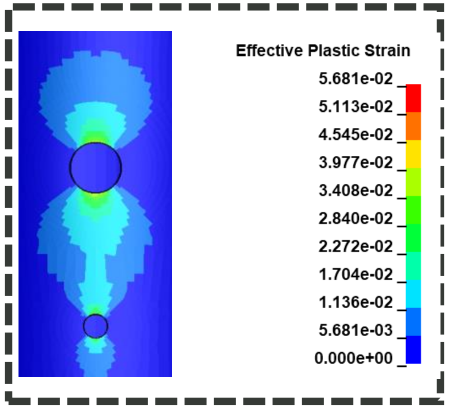
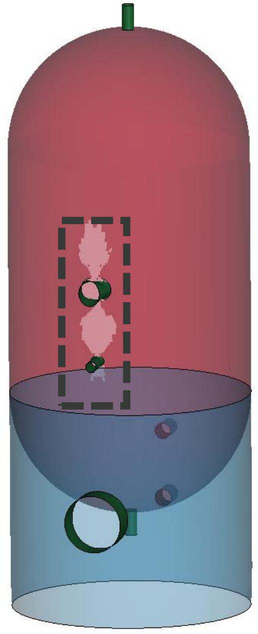
Fire Response Assessment Results

Scenario	Fill Level (%)	Heat Flux (kW/m^2)	PFP (Pressure Vessel / Saddle)	Maximum Pressure and Pressurization Time in Analysis	Failure Mode	Time to Fail (sec.)	Mid-surface Temperature at Failure (°C)
Case 1 (Pool Fire)	75	150	No / Yes	280 psi in 3.5 min.	Rupture around nozzle at the top	53.05	555
Case 2 (Pool Fire)	75	100	No / Yes	280 psi in 3.5 min.	Rupture around nozzle at the top	59.15	566
Case 3 (Jet Fire)	75	300	No / Yes	280 psi in 3.5 min	Rupture around nozzle at the top	48.85	579
Case 4 (Pool Fire with Depress.)	100	150	No / Yes	100 psi in 15 min(1)	Rupture around manhole at mid-height	56.40	548
Case 5 (Pool Fire)	75	25	No / Yes	140 psi (normal operating pressure)	No Failure	N/A	N/A



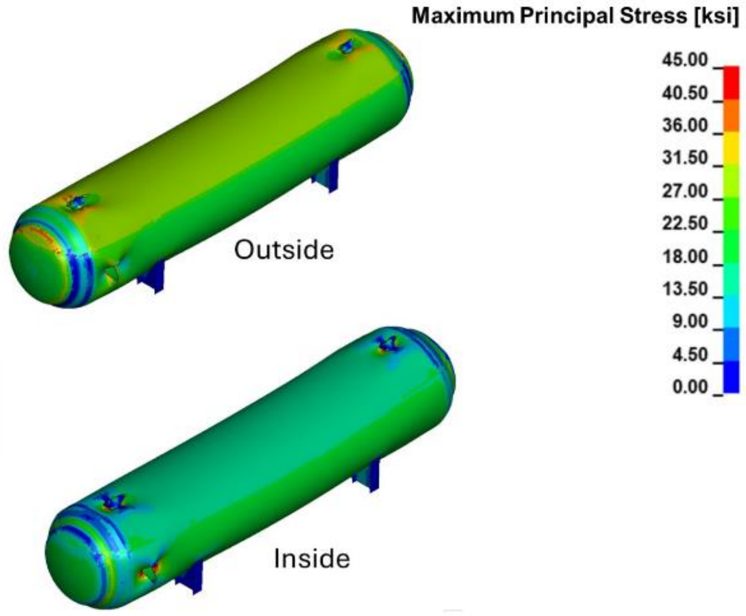


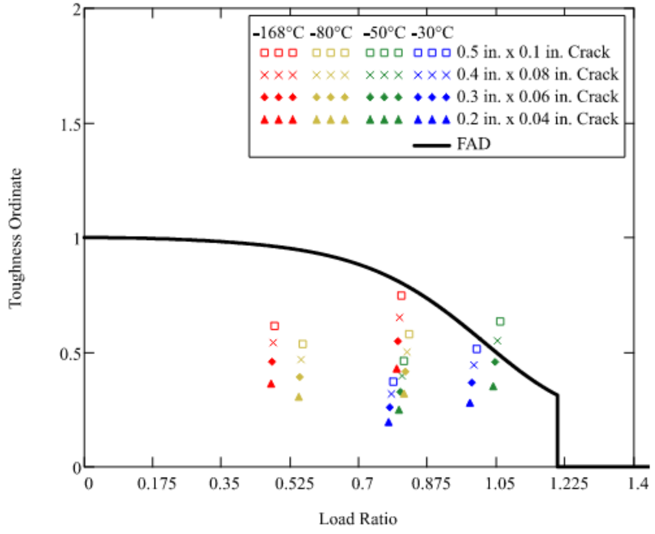




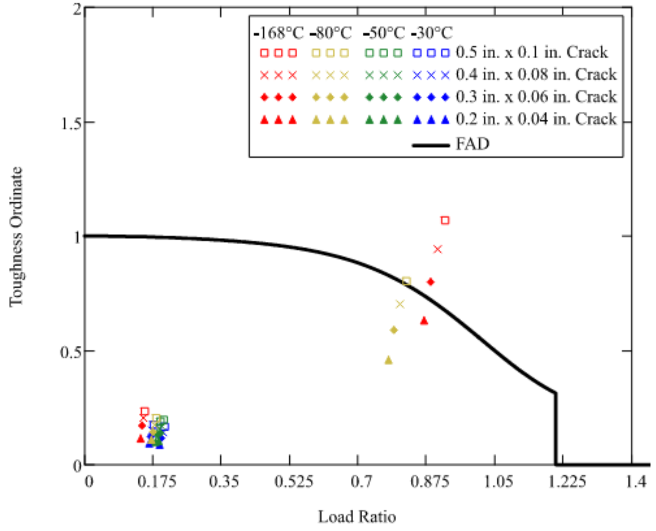
EQUIPMENT RESPONSE ASSESSMENTS

Cryogenic Release Response Assessment Results

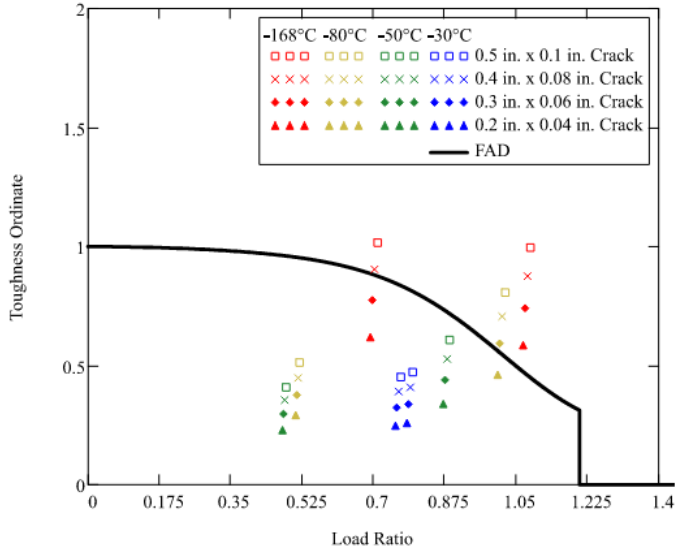




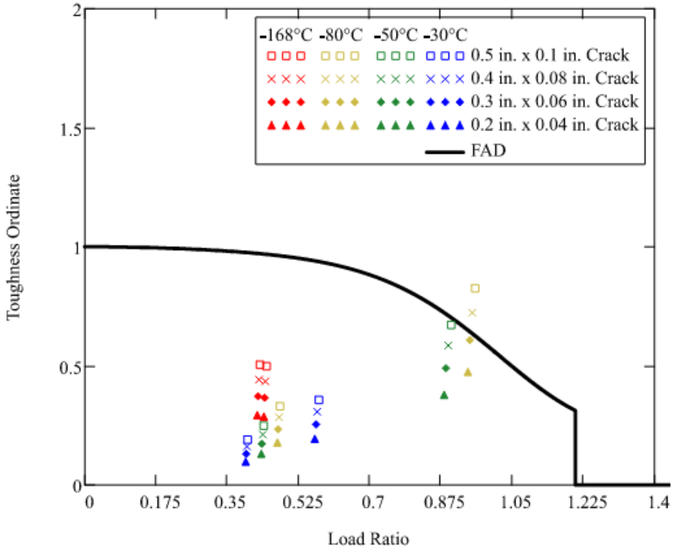
FAD for Long. Flaw Cases in Vessel Body



FAD for Circ. Flaw Cases in Vessel Body



FAD for Merid. Flaw Cases in Vessel Head



FAD for Circ. Flaw Cases in Vessel Head

STEEL STRUCTURES RESPONSE ASSESSMENTS

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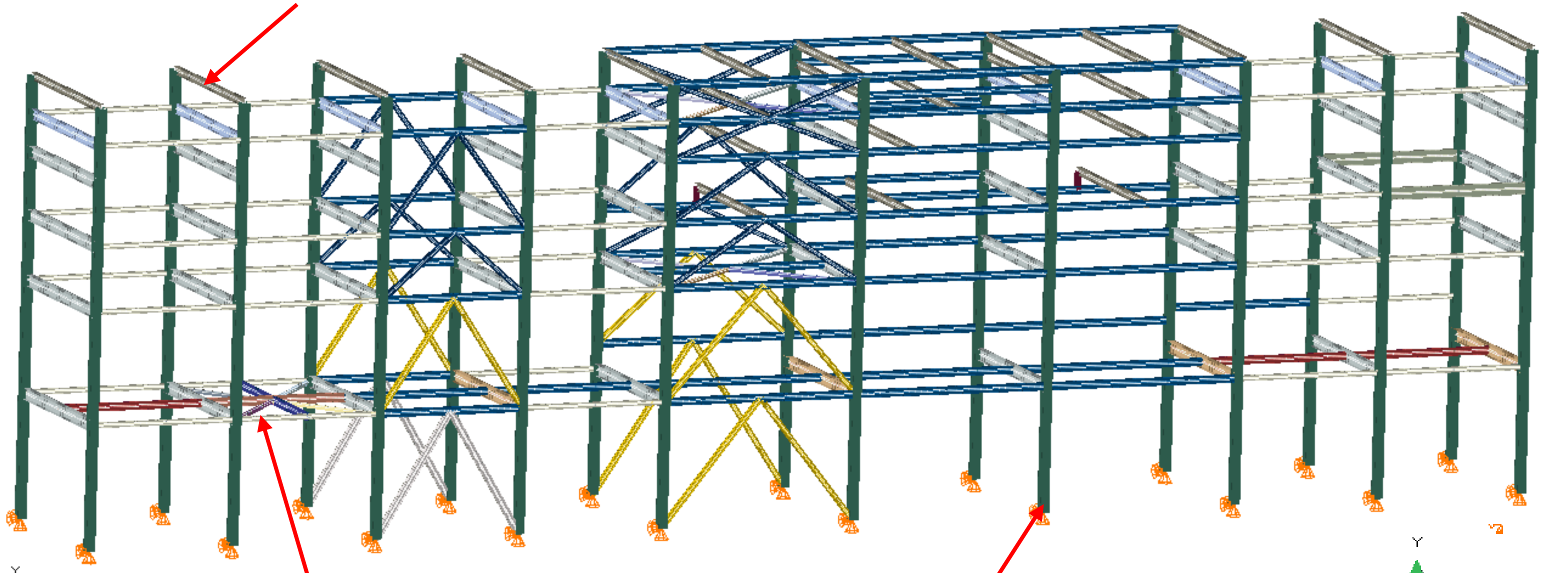
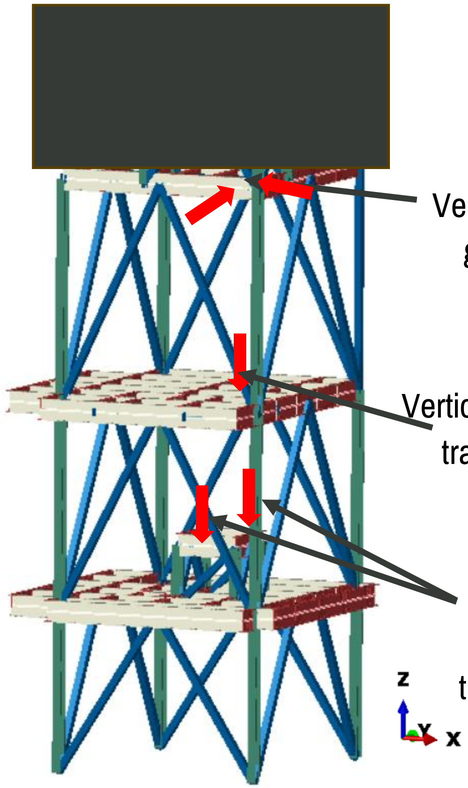
Piperack FE Model

- Height = 57 ft (17.4m), length = 197 ft (60m), width = 24.6 ft (7.5m)
- First three levels support piping
- Top two levels support cable trays
- Operating loads including live loads as per PIP STC01015

Equipment Support Structure FE Model

- Height = 69 ft (21m), length = 20.3 ft (6.2m), width = 25 ft (7.6m)
- Horizontal equipment is 13 ft (4 m) long with 2.7 ft (0.8 m) diameter
- Vertical equipment is 56 ft (17 m) long with 3.3 ft (1 m) diameter





STEEL STRUCTURES RESPONSE ASSESSMENTS

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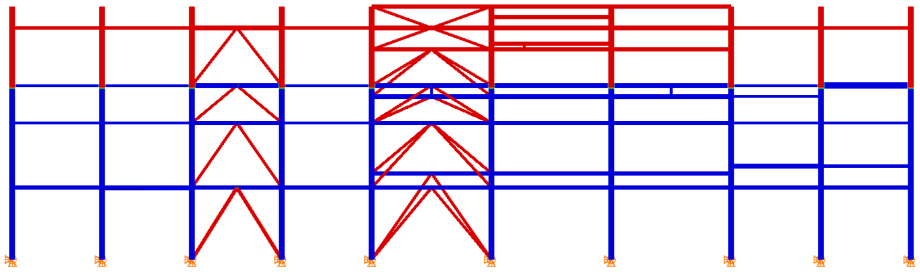
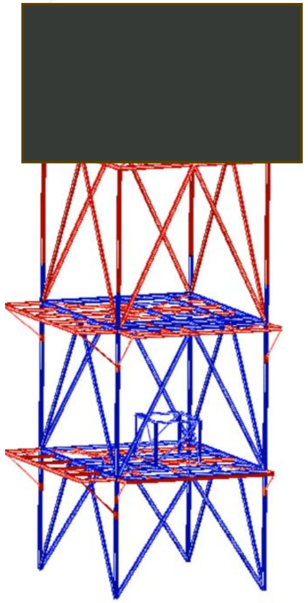
Passive Fire Protection (PFP) in API 2218

FIREPROOFING PRACTICES IN PETROLEUM AND PETROCHEMICAL PROCESSING PLANTS 7

Table 1—Dimensions of Fire-Scenario Envelope

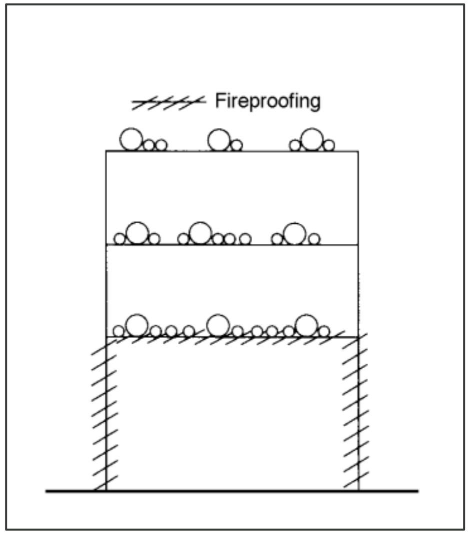
Hazard Concern	Horizontal	Vertical	Section in API 2218 or other Reference
A fire-scenario source of liquid fuel release—general	20 to 40 ft (6 to 12 m)	20 to 40 ft (6 to 12 m)	5.2.3
Fire-potential equipment	20 to 40 ft (6 to 12 m)	Up to highest level supporting equipment	6.1.1.1
Nonfire-potential equipment Above-fire potential equipment	20 to 40 ft (6 to 12 m)	Up to level nearest 30 ft (9 m) above grade	6.1.1.3
LPG vessels as potential source of exposure	Pipe supports within 50 ft or within spill containment area	Up to level nearest 30 ft (9 m) above grade	5.2.3, API 2510
Fin-fan coolers on pipe racks within fire-scenario envelope	20 to 40 ft (6 to 12 m)	All support members up to cooler	6.1.2.2, 6.1.3
Rotating equipment	20 to 40 ft (6 to 12 m) from the expected source of leakage	20 to 40 ft (6 to 12 m)	5.2.3
Tanks, spheres, and spheroids containing liquid flammable material other than LPG	The area shall extend to the dike wall, or 20 ft (6 m) from the storage vessel, whichever is greater.	20 to 40 ft (6 to 12 m) or as specified for equipment of concern	5.2.3
Marine docks where flammable materials are handled	100 ft (30 m) horizontally from the manifolds or loading connections	From the water surface up to and including the dock surface	

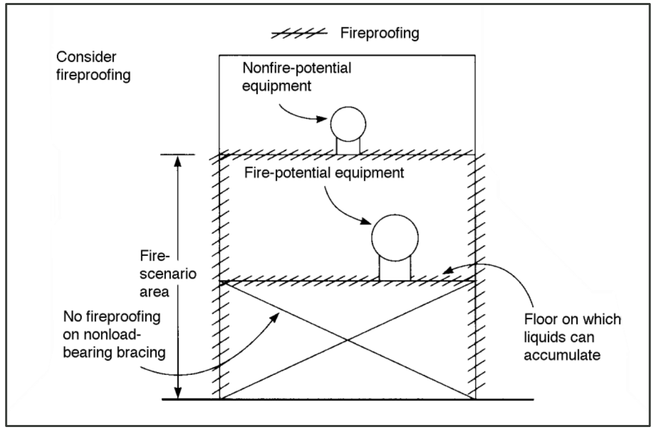




Members protected with PFP

Unprotected members

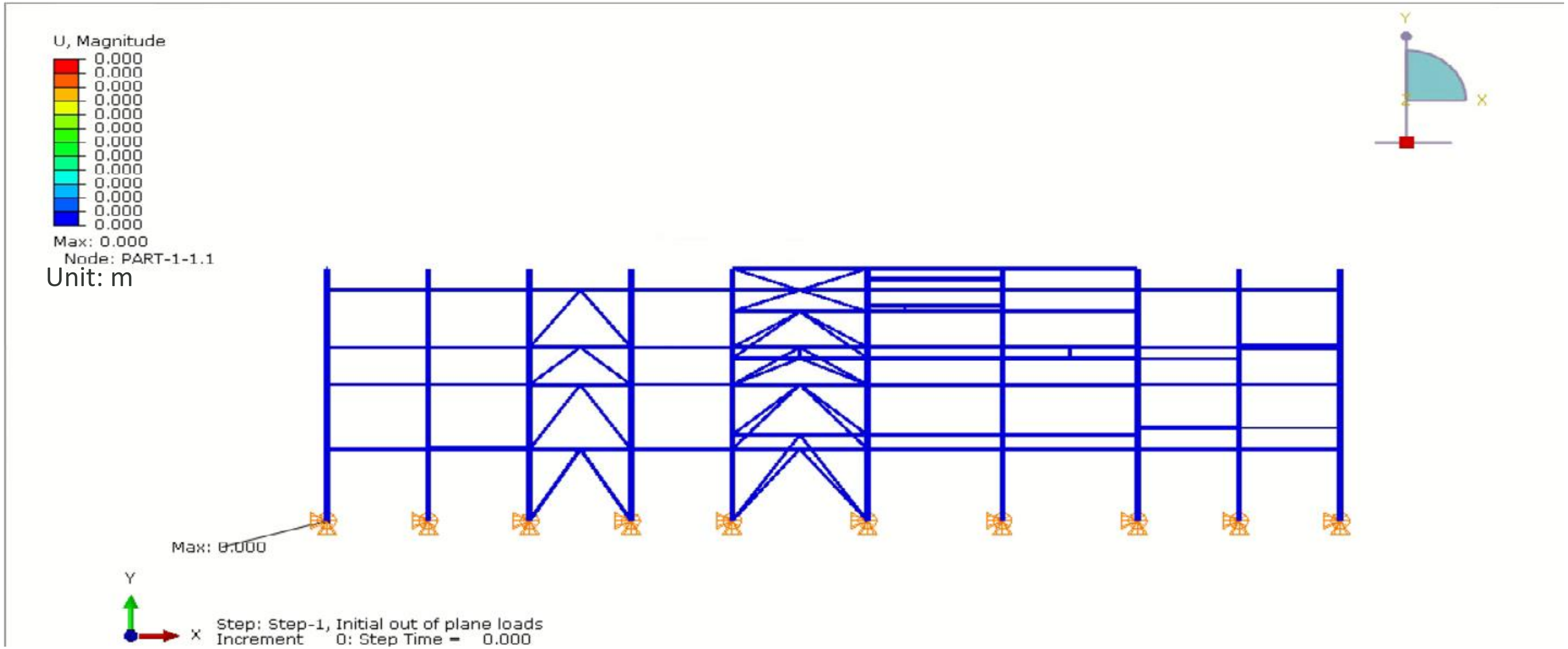




Case	PFP Applied	Output Variable	Analysis Case Notation
Heat-up	Y	Failure Temperature	HP-T
		Reserve Strength Ratio	HP-C
		Reserve Strength Ratio	HF-C
	N	Failure Temperature	HU-T
		Reserve Strength Ratio	HU-C
Heat-up Followed by Cooldown	Y	Residual Strain	CP-E
		Reserve Strength Ratio	CP-C
	N	Residual Strain	CU-E
		Reserve Strength Ratio	CU-C

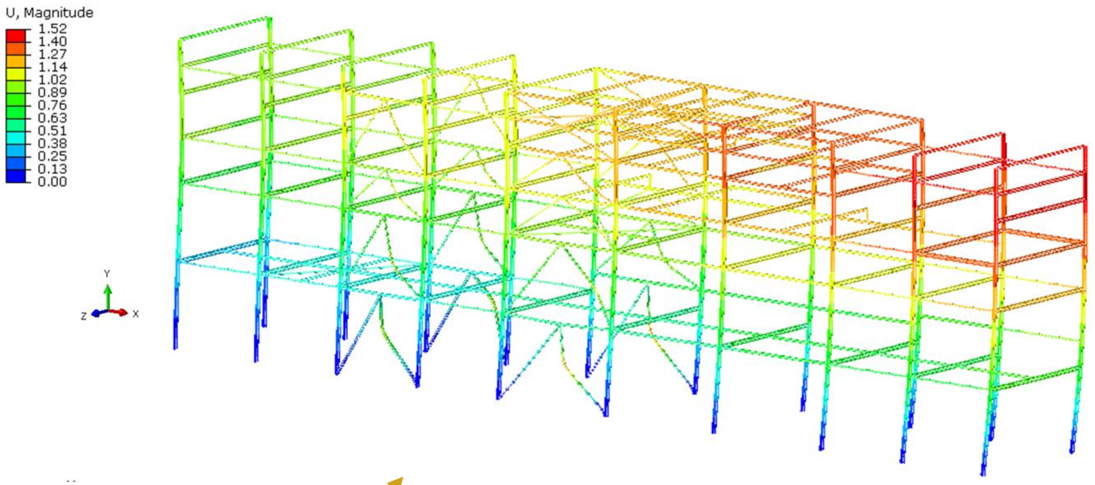
Piperack – HU-T

- Failure captured at the last frame of animation
- Column buckling causes collapse



STEEL STRUCTURES RESPONSE ASSESSMENTS

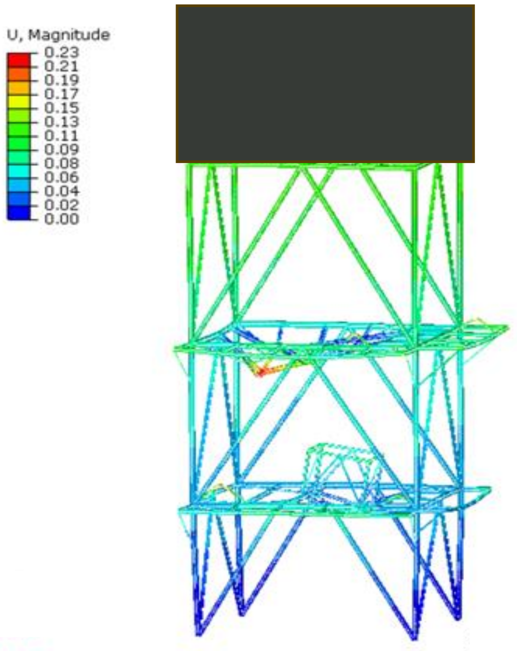
Fire Response Assessment Summary



Analysis Case	Failure Temperature (°C)
HU-T	769
HP-T	790

Analysis Case	Reserve Strength Ratio
HF-C	5.4
HP-C	1.4

Analysis Case	Reserve Strength Ratio
CU-C	9.6
CP-C	9.7

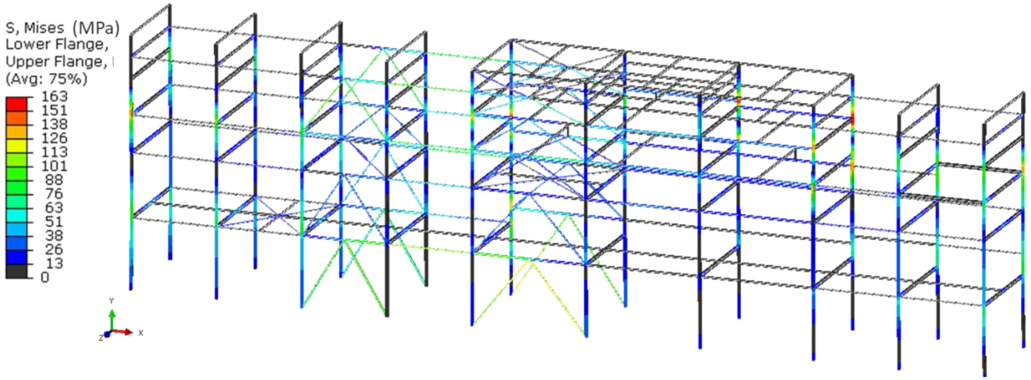


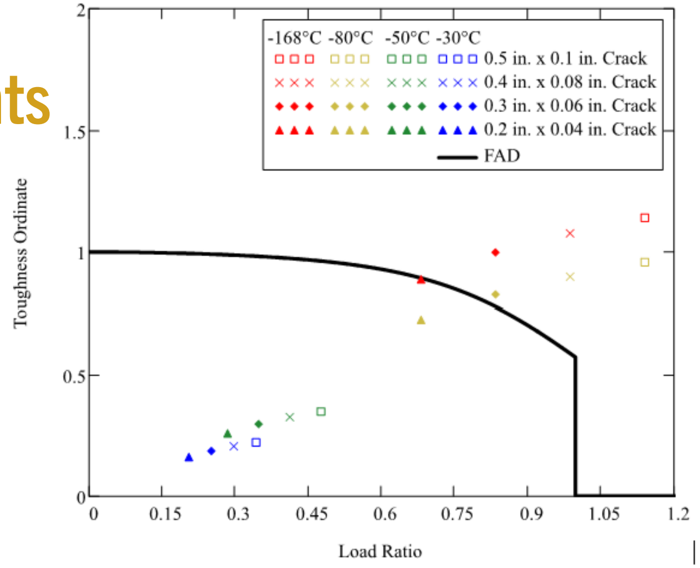
Analysis Case	Failure Temperature (°C)
HU-T	694
HP-T	950

Analysis Case	Reserve Strength Ratio
HF-C	3.3
HP-C	1.6

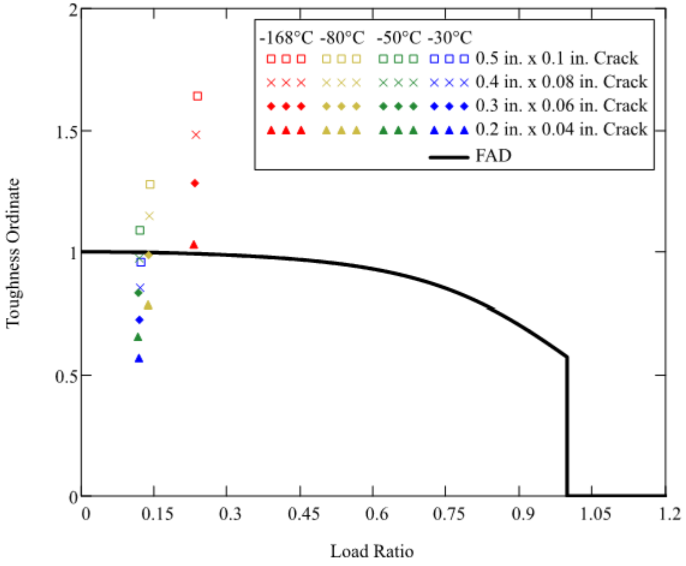
Analysis Case	Reserve Strength Ratio
CU-C	4.0
CP-C	4.1

Cryogenic Release Response Assessments

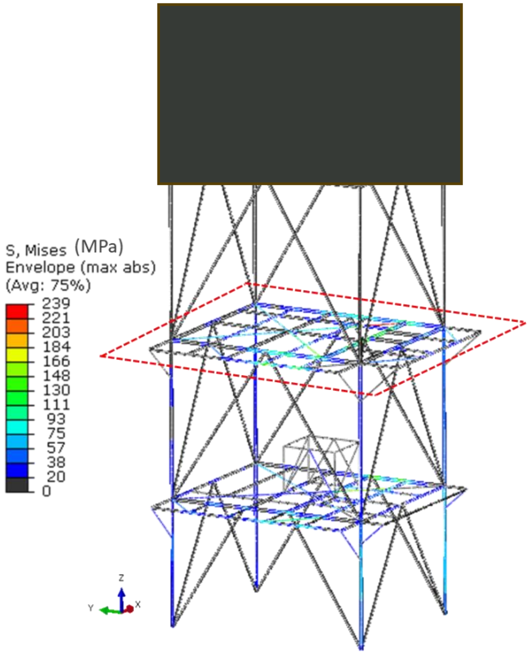


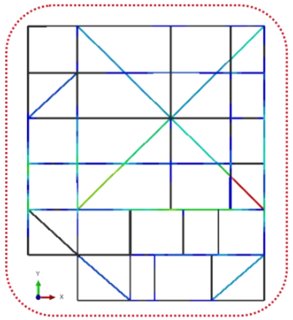


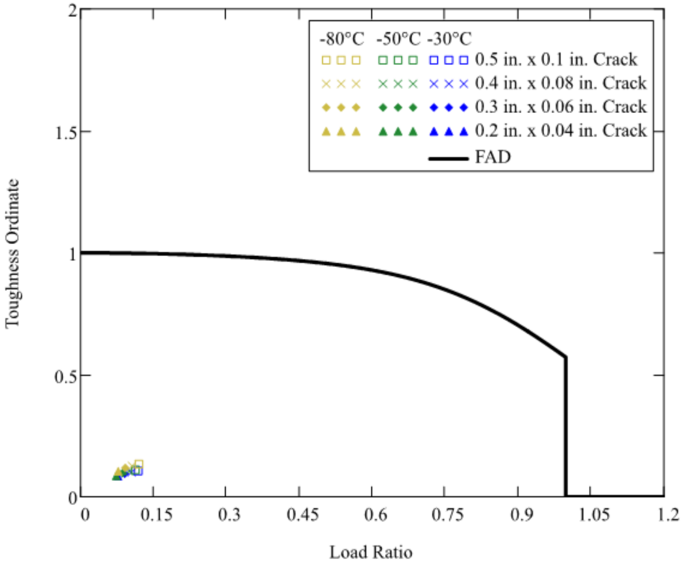
FAD for Flaws in Brace Webs at Brace-Column Connections in Piperack



FAD for Flaws in Beam Flanges at Beam-Column Moment Connections in Piperack



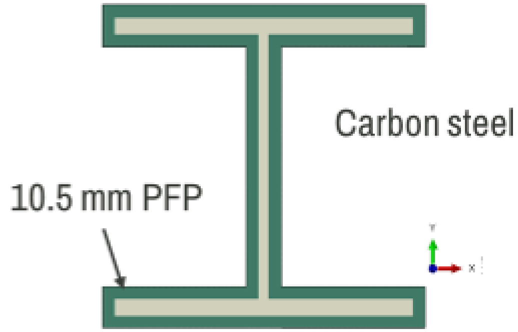




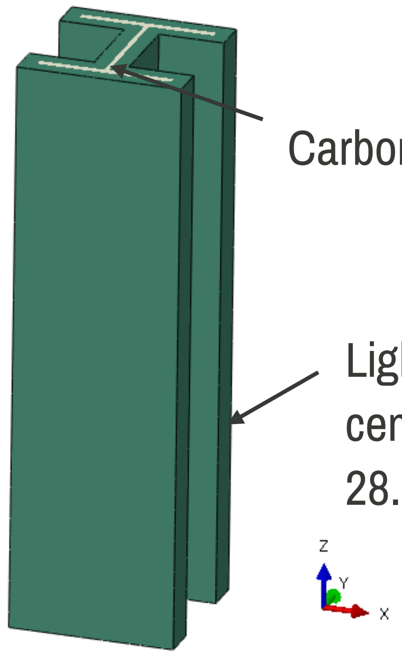
FAD for Flaws in Beam Webs at Beam-Column Shear Connections in Equipment Support Structure

FE Model and Analysis Scenarios

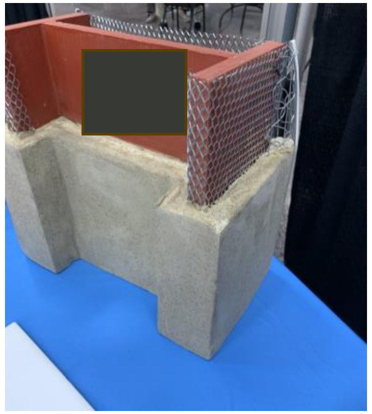
- We analyzed a 1 m long W10x49 column section with
  - Lightweight cementitious PFP
  - Intumescent PFP
- Fire scenarios
  - Pool fire up to 2 hour
  - Jet fire with 200kW/m^2 heat flux for 30 min.
  - Jet fire with 350kW/m^2 heat flux for 60 min.
- Cryogenic release scenario
  - Liquid spill and jet release
- We used temperature-dependent thermal properties
- We performed transient heat transfer analysis



W10x49 section with intumescent PFP



W10x49 section with cementitious PFP



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Cementitious PFP – Fire and Cryogenic Release Cases, Properties, and Analysis Results

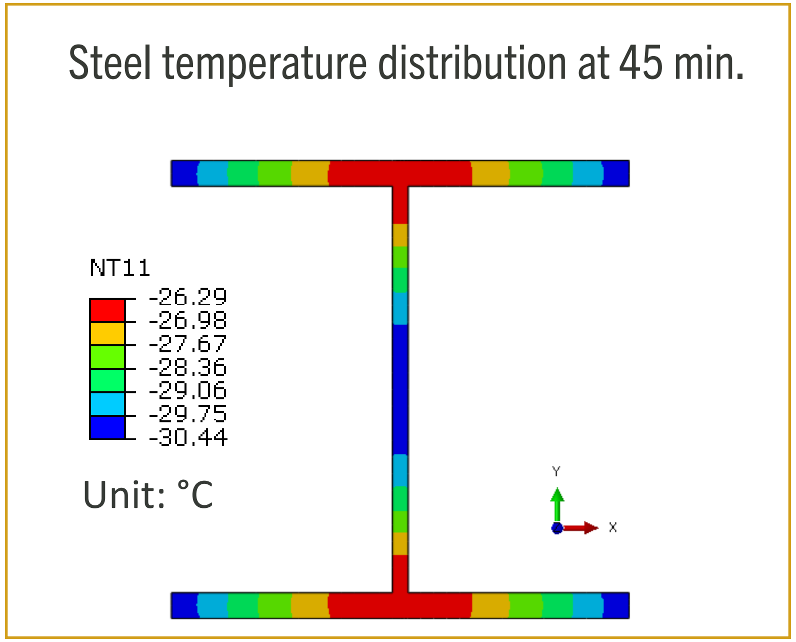
- H120 rated PFP, PFP thickness = 28.575 mm (1.125 in.)
- Specific heat of cementitious PFP = 1507 J/kg-K (product datasheet)

Thermal Properties			
	Lightweight Cementitious PFP	**Steel**	
Load case	**Thermal Conductivity (W/m-K)**	**Thermal Conductivity (W/m-K)**	**Specific Heat (J/kg-K)**
Fire	Constant value of 0.125 (product datasheet)	Temperature dependent per EN 1993-1-2: 2005	
Cryogenic Release	0.25 at -168°C to 0.125 at 20°C	60 at -168°C to 51 at 20°C	236 at -168°C to 425 at 20°C

NOTE: Properties of PFP at -168°C is extrapolated from EN 1992-1-2: 2004 and for steel at -168°C is extrapolated from EN 1993-1-2: 2004.

Maximum Steel Core Temperature with Cementitious PFP		
Pool fire	**Jet fire with 200kW/m² heat flux**	**Jet fire with 350kW/m² heat flux**
At 2hr.	At 30 min.	At 60 min.
477°C	125°C	340°C

W10x49 Temperature Profile



Cryogenic Release Response

Intumescent PFP – Fire and Cryogenic Release Cases, Properties, and Analysis Results

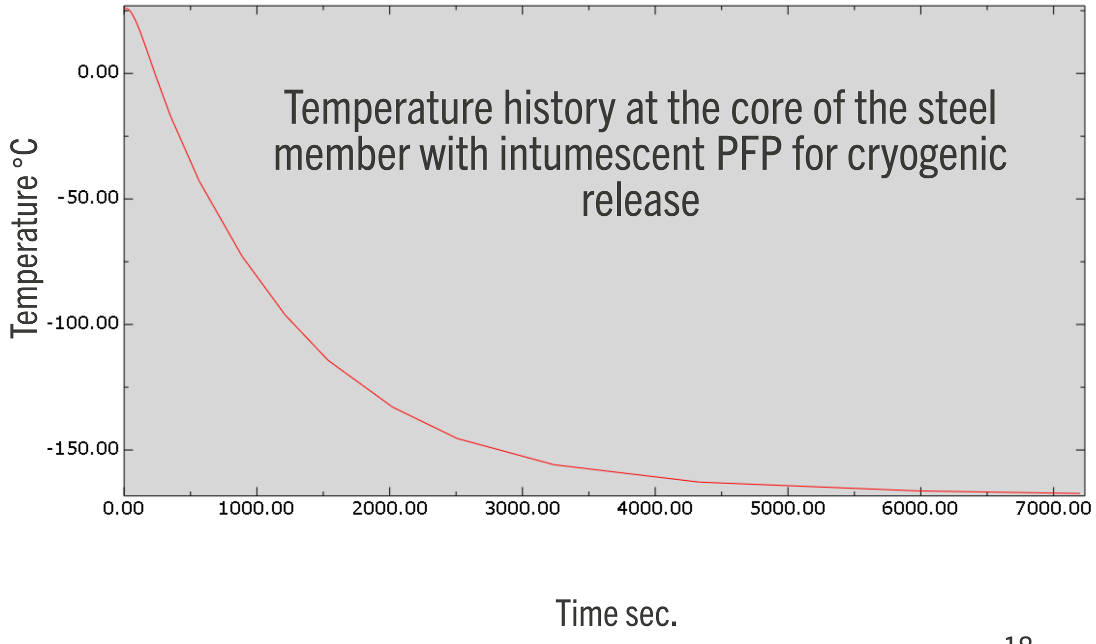
- H120 rated, thickness = 10.5 mm (0.4 in)
- Emissivity = 0.92 and convection coefficient = 25 W/m^2-K

Epoxy-based Intumescent PFP Thermal Properties			
Load Case	Effective Thermal Conductivity (W/m-K)	Specific Heat (J/kg-K)	Effective Density (kg/m^3)
Fire	0.02*	1000	100*
Cryogenic Release	0.2	1000	1000

* Effective thermal conductivity and effective density of the PFP material is accounting for the expansion of the intumescent coating and charring. We consider 10 times expansion of the coating for pool and jet fires (without thickness loss).

Maximum Steel Core Temperature with Intumescent PFP		
Pool fire	Jet fire with 200kW/m^2 heat flux	Jet fire with 350kW/m^2 heat flux
At 2hr.	At 30 min.	At 60 min.
387°C	160°C	310°C

- Cold penetrates at a higher rate in the member with intumescent PFP due to the lower coating thickness
- The steel member with intumescent PFP takes less than 10 minutes to reach -30°C
- NFPA 59A (2019) lists a minimum of 10-minute duration if the process design includes acceptable detection, isolation, and shutdown



RECOMMENDATIONS

- Methodology
  - Ductility level analysis for fire response or stress analysis followed by FFS assessment for cryogenic release response
- Hazard Analysis
  - Detailed facility specific fire and cryogenic risk studies and consequence-based approaches covering a range of release scenarios, such that impacts are bounded
  - Important to recognize that a worst-case scenario is not always immediately apparent. The characterization of the impacts and extent of the cryogenic spray hazards to be used in the assessments need further research
- PFP / CSP Systems
  - Transient heat transfer analysis followed by a structural response analysis or a coupled thermal-structural analysis
  - Temperature thresholds
  - Need for CSP systems and ratings should be based on engineering assessments to establish ductile to brittle transition limits

RECOMMENDATIONS

- PFP / CSP Systems (Continued)
  - Other considerations
- Pressure Vessels and Steel Structures
  - Protect pressure vessels with relatively thin shells using qualified PFP
  - Analysis considering the facility specific hazard scenarios, structure configurations, and operating loads in making decisions on protecting important structural elements
  - Case-by-case evaluation of the endurance limits for piping, equipment, and structures without PFP and CSP as the response depends on section sizes, geometry of the structure, detailing, and utilization
  - A comprehensive design approach involving process safety, structural, mechanical, and materials technology disciplines from the early stages to develop efficient and safe solutions

DISCUSSION / QUESTIONS

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