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Advanced Fire Integrity Analysis and PFP Optimization Methods for Petrochemical Facilities

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Abstract

Design of process modules, piperacks and occupied structures for accidental fire loads is critical for a facility's operation, emergency planning, safe shutdown and evacuation strategy. In the oil and gas industry, hydrocarbon fire scenarios with high thermal loading should be accounted for. These accidental fire loads can be critical during the design phase. Recent improvements in fire analysis and design methodology for structures, piping systems and equipment are discussed in this study in regard to performance-based applications. Acceptance criteria for performance-based fire design have not been well documented in the literature. Prescriptive approach, utilization checks, limiting core temperatures, and deflection ratios or plastic strains for ductility level analysis are used as the basis of fireproofing requirements in the industry typically. However, actual response of safety critical elements supported by the subject structural members is typically not taken into account directly. Different acceptance criteria and response of supported piping systems are presented through case studies in this paper. Also, practical aspects of fire protection including three sided PFP application and coat-back optimization are discussed. For the structural fire integrity assessment, heat transfer and structural fire response analyses were performed utilizing USFOS and ABAQUS software packages.

Performance-based approach in fire response design of offshore and onshore structures has been successfully implemented using advanced numerical analysis tools and close collaboration between Safety, Structural, Construction and Operations teams. This approach involves an iterative analysis procedure considering interaction of load bearing (structural) and

other systems (piping, electrical etc.). The refined analysis and optimization process ensures that PFP is only applied to critical structural elements and fire performance of protected systems are verified through analysis. In addition to reducing the risk, this in turn precludes an overly conservative design recommending application of PFP in a broader area without analytical justification.

The main advantages of reducing application of PFP coating on non-critical members and equipment are cost savings and integrity management improvements during life cycle of a facility due to issues such as corrosion under insulation and long-term inspection and maintenance. Considering the fact that CAPEX and integrity management are major concerns for most structures at petrochemical facilities, optimization of PFP for plant structures has significant benefits for operators and owners of onshore and offshore assets. The integrated structural, foundation and equipment and piping systems fire analysis approach presented in this study is considered to be a significant addition to state of the art in fire protection design of oil & gas and petrochemical facilities. Improvements in analysis and design methods are expected to result in application of PFP at the critical locations only without compromising from safety requirements. This also ensures that safety critical elements are protected against credible hydrocarbon fire scenarios.

1. Introduction

Over the past few decades, steady increase in the consumption of energy has demanded for development of new facilities for oil and gas extraction and processing; both offshore and onshore. Due to the intrinsic nature of the Oil & Gas industry, fire is one of the main hazards threatening life and assets. When subjected to high thermal loading, the strength of structural components and safety critical equipment, piping and vessels degrade. The exact response and associated risk of potential escalation due to hydrocarbon fire depends on interaction between duration of fire event, heat flux, material properties, and the structural configuration. Therefore, risk assessment is essential for understanding the accident scenarios and for survival of structure and reducing vulnerability. This is also important for the development of appropriate mitigation solutions during every phase of a design project and repair planning during service life.

Several design standards around the world, such as American Petroleum Institute (API) [1] [2], British Standards (Eurocode) [3], and Det Norske Veritas (DNV) [4], recommend the use of active and passive fire protection systems for mitigation against accidental fires for offshore platforms and onshore plants. An active fire protection (AFP) system is a group of systems that require some amount of action or motion in order to work efficiently in the event of a fire, such as fire water deluge or sprinklers. On the contrary, a passive fire protection (PFP) is a structural and non-structural component that control the spread of fire and prevent or delay the collapse of structure/compartments such as firewalls and fire-retardant coatings. For safety critical structures, piping systems, vessels, and equipment PFP application is commonly utilized as a fundamental risk mitigation strategy.

During the pre-FEED and FEED stages of a design project, the PFP requirements for a structural component or safety critical equipment is based on simplistic/deterministic assumptions, standards, and empirical calculations [3, 5]. With the evolution of project, more sophisticated methods such as that outlined in Fire and Blast Information Group (FABIG) Technical Note 11 [5] is often employed. The outlined methodology is a two-fold procedure: (1) Fire Risk Assessment (FRA), and (2) thermal-structural collapse analyses. FABIG [5] has also set out methodology to perform a detailed FRA to calculate Design Accidental Load (DAL). In this procedure, a risk-based approach is adopted to calculate DAL that takes into consideration of the probability of a fire event on the basis of the cumulative frequency of each fire scenario and the risk acceptance criteria. The obtained DAL is then utilized to assess the response of a structural system subjected to accidental fire loading. This analysis provides insights into the failure mechanism and structural collapse time for a given fire scenario that is used then to develop fire mitigation solutions as per process safety critical elements' survival duration requirements. Response information obtained from the aforementioned analysis is then utilized to determine the location and rating of PFP requirements for a facility.

Several research studies have been published on FRA methods [6, 7, 8, 9, 10]. These studies only estimate the risk associated with fire events. Very few researchers have considered FRA in conjunction with PFP requirements and optimization. For example, Shetty et al. [11] presented a theoretical method by utilizing probabilistic FRA to estimate the optimal design of PFP on offshore structures. De Sanctis et al. [12] proposed a reliability-based model to quantify the level of safety of prescriptive and performance-based steel building designs. Some researchers took experimental approach to assess the PFP requirements [13]. However, the use of large scale Finite Element Analysis (FEA) packages for determination and optimization of PFP is virtually lacking in literature. Hunt et al. [14] in 1997 utilized FEA to calculate the area and thickness requirements for PFP coating of the primary steel for the deck of the Mars Tension Leg Platform. In their work, the location of jet fire and pool fires were identified from a hazard analysis, which was utilized to calculate temperature flow of affected members of the primary members of the topsides as a function of time through heat transfer analysis. They found that that the temperature flow into the coated steel member is largely dependent on the thickness and composition of PFP coating. The "Zone" method of design in combination with 0.2% of strain assumption was employed to calculate the maximum allowable temperature for a critical structural member. The "Zone" method of design assigns a maximum allowable temperature that can develop in a steel member without reference to the stress level in the member prior to the fire [1]. To estimate the required PFP thickness and quality for the primary steel members due to localized jet fire under normal operating load conditions, ultimate strength analysis of the topsides was performed using USFOS FEA software package [15].

Similar techniques have been repeatedly reported for the optimization of PFP coating on steel structures [16, 17]. The common approach utilized in all these studies is to estimate fire loading scenarios using FRA followed by scenario based thermal structural analysis using USFOS. In the adopted procedure, progressive structural collapse analysis under thermal loading is performed by modeling an isolated structure with operating loads applied. The temperature dependent mechanical and thermal behavior of steel is captured by using the guidelines specified in FABIG [18] and Eurocode [3]. Through a series of thermal-structural collapse analysis, one or several coated members are removed, iteratively, from the protected members group to eliminate redundancy in PFP coating. Though this is useful during pre-FEED and FEED phase of a design project, such an approach often leads to conservative estimation of PFP coating requirements. The conservatism is attributed to the following reasons:

- The thermal-structural analysis does not account for the fire durations established through FRA studies;
- The assessment method takes the heat affected area into consideration in complete isolation without giving any credit for the possible escalation of hazard due to failure of any safety critical systems, such as piping, equipment, and collapse of neighboring structure;
- The loads due to processing equipment and systems are always active during the numerical simulation, irrespective of whether failure of a structural member has occurred or not. This does not take into consideration of possible loss of equipment/pipe support and subsequent redistribution of load.

To this end, authors propose a new more advanced methodology that attempts to eliminate the aforementioned deficiencies found in the commonly adopted approach. In the present work, we developed a PFP optimization method by adopting a multi-disciplinary approach to achieve a performance-based PFP scheme. In this, we perform non-linear thermal-structural analysis for whole topsides or a processing unit as one structural system. All process safety critical equipment and piping along with any neighboring structure are included in the FE Model. The temperature time history is obtained by a separate heat transfer analysis for both protected and unprotected members individually, which is later utilized in the stress analysis for the performance assessment and PFP optimization. In this study, we have taken advantage of the state of art ABAQUS FEA software package [19] which offers robust modeling capabilities as well as the capability to perform large scale simulations in short time. The proposed methodology is not only useful during detailed design phase but also can be utilized during the construction and execution phases of a project. Furthermore, the developed methodology can also assist in repair works during the operation of a facility.

2. Performance-based PFP Optimization Approach

Typical Passive Fire Protection Materials

For fire risk mitigation based on the result of Fire Integrity Assessment (FIA), Passive Fire Protection (PFP) materials are frequently applied to the structural members that are critical to prevent consequential hazards; i.e. contributing to the global stability and load-bearing in addition to integrity of safety critical elements.

Commonly used PFP types for structural members are Epoxy intumescent and lightweight cementitious types. Both are applied as a spray-coating to the substrates. Epoxy intumescent PFP materials contain thermally active chemicals for fireproofing. This type of PFP material is expands several times their volume when exposed to heat to form a protective char at the barrier that faces the fire [2]. Cementitious type PFP is another typical fireproofing material for the structures in relatively benign areas. However, cementitious PFP material may absorb relatively high moisture between the PFP layer and the substrate so that corrosion under fireproofing may bring problems for the steel structures [20]. Flexible Blanket type or endothermic warp type PFP are particularly suited for process equipment, piping systems, electrical cable trays or repair projects on operating plants. These are applied by surrounding the substrates with a couple of composite panels or multiple layers. These materials can be directly added on to the existing insulations for fire protection purposes. For outdoor applications and protection against jet fire abrasion, stainless cladding or mesh is typically provided at the outer surface with proper fixation methods [2].

Performance-based Fire Integrity Assessment

Performance-based approach for FIA allows to understand structural fire response in rational basis and to estimate thermal capacity of the structures more accurately than prescriptive approach [2]. Following the performance-based approach for FIA, thermal response of the structural components subjected to fire loading should be defined, and PFP application to structural members shall be based on their relevance to global stability and criticality in terms of supported elements; i.e., process safety equipment such as vessels, piping and instruments. Since structural fire response is a complex problem [21], interaction of critical load carrying structural members and consideration of load redistribution during an accidental fire event should be taken into consideration. Therefore, a non-linear inter-disciplinary FIA is necessary for the engineering and optimization of PFP application.

For a reliable structural response, a multi-disciplinary approach has to be adopted while considering several important variables; such as impairment frequency, fire duration, leak probability, thermal material properties of the substrate and fireproofing material, and mechanical properties of the structural member, etc. From the structural reliability point of view, thermal material properties such as specific heat capacity, density, and thermal conductivity are essential to calculate temperature gradient for a structural member subjected to accidental fire loading. Eurocode [3] and FABIG [18] provide temperature dependent material properties for carbon steel and stainless steel. Flame emissivity, surface radiation emissivity, and convective heat transfer coefficient are, also, the important parameters that govern the response of a structural system depending on the fire type and the flame condition. The expected flame condition for hydrocarbon fire can be modeled according to the guidelines provided in Eurocode [3, 22] and API [1]. Thermal material properties of PFP vary by the product. These recommendations help in modeling a realistic response for a structural member, when applied, thanks to low thermal conductivity and high specific heat capacity of the PFP materials. It is worth noting that proper modeling of thermal behavior of the applied PFP is of utmost importance in order to estimate accurate thermal reaction of the structural components with PFP when subjected to accidental high temperature loading conditions.

Deterministic Fire Integrity Assessment

During the initial phase of project, the application of PFP is based on deterministic fire scenarios based on industry standards or consequence analysis. Process areas are grouped into fire zones and fireproofing is specified accordingly. In the fire integrity analysis, load cases and load factors are adopted from API RP-2FB. It is assumed that PFP is fit for purpose and can maintain core temperature of structural steel below 400°C for the specified duration. Commercial non-linear Finite Element Analysis (FEA) software packages such as USFOS [15] are used for analysis of process modules and piperacks included in the PFP scope. In these assessments, since the PFP is assumed to be fit for purpose the core temperature of protected element is limited to 400°C; though this could be conservative for some members that may remain well below this limiting temperature. Additionally, non-linear behavior of frame members is captured by using a temperature dependent material model, and by accounting for non-linear geometry effects. For example, beam can yield when overloaded and columns can buckle (elastically or plastic) when overloaded. The ductility level analysis allows for load redistribution and prediction of structural failure times. In the analysis, failure is defined as excessive deformation of members supporting process safety critical elements (piping, valves etc.) or global failure such as collapse due to instability. Several iterations are performed by reducing the number of protected members until an optimized PFP scheme is obtained.

Risk-based Fire Integrity Assessment

Probabilistic Fire Risk Analysis Workflow

When the facility's design is matured, i.e., detail design phase, jet fire probabilistic data and fire impact exceedance frequencies can be calculated, and the probabilistic assessment of the facilities can be conducted for PFP requirement optimization. In the probabilistic assessment, fire load characteristics and the substrate thermal capacity are considered. Fire load characteristics such as release location, duration, and possible orientation are included in the risk-based fire scenario assessment. CCPS [23] provides one of the most widely accepted methodologies for the fire risk assessment. The methodology is also in line with other guidance such as Norsok Z-12 [24], FABIG TN 11 [5], API RP 14G [25] and 2FB [1], and UKOOA [26].

Figure 1 illustrates the overall Quantitative Risk Assessment (QRA) process for fire accident. Fire load characteristics and ignited event frequencies are extracted from the mature QRA model. Fire events are evaluated against structural impairment criteria that is determined through detailed structural analysis. Fire characteristics such as release location, duration, and possible orientation are considered in the FRA. Ignited event frequencies are also extracted for each scenario, which are further modified to determine cumulative impact event frequencies for individual points in 3D space. Figure 1 illustrates the detail procedure for FRA to identify design fire loads. Eventually, this process identifies the locations where the cumulative impact event duration exceeds the thermal capacity of a structure.

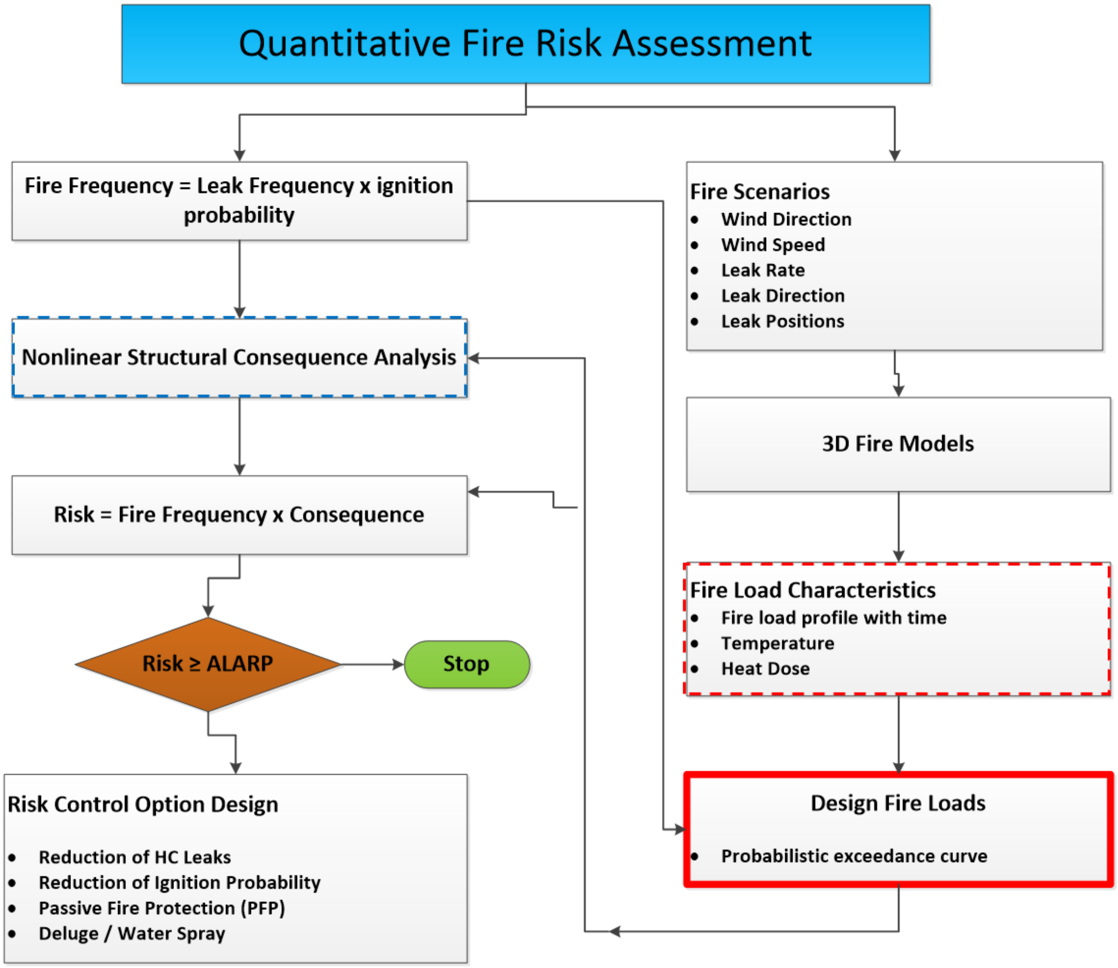


Figure 1. Overall QRA Workflow

Thermal Capacity of Structures

Thermal capacities of structures are established and refined through coupled structural-safety critical system fire response analysis. The structural failure time is determined through structural analysis, iteratively to estimate impairment durations for a fire scenario. This calculated failure time is subsequently utilized to evaluate the impairment frequency.

Structural exposure durations for thermal radiation levels vary depending on the fire zone. In general, the thermal radiation and the corresponding exposure durations are lower at higher elevations. However, the height of the fire zone can be extended for open steel beam structures based on project safety requirements. Conservatively, structural models may be evaluated in its entirety with target thermal radiation level and, typically, for a period longer than actual fire duration to ensure a complete understanding of any potential structural impairment, especially after the accidental fire events such as during cooling phase.

Figure 2. Design Fire Load Calculation Procedure

Fire Load Characteristics

All of the relevant inventories and fire scenarios from the QRA are evaluated for their potential to impact any given point in the target structures. Both pool and jet fire types are considered. Based on close review of the relevant inventories, the most likely discharge height and location for each inventory are identified. Releases from large process piping systems are assigned to multiple points so as to distribute the inventory release/ impact frequencies. Multiple release orientations are considered under all weather conditions to determine the most conservative length and width of flame envelope and radiation contour dimensions. The most conservative dimensions of each are combined into a single scenario for further analysis. Each of these dimensions are not necessarily from the same release orientation or weather condition. Flame envelope and thermal radiation contours are handled slightly differently in order to calculate the 3D impact frequency.

Cumulative Event Frequency

Using a 3D approach common to that used for offshore platforms, individual event frequencies are calculated by determining the proportion of a spherical surface area that is enveloped by the fire or thermal radiation contour shape approximation. The radius of the hypothetical sphere is assigned as the distance from the release orifice to the impact location of interest. Dimensions of the thermal contours are not modified. Therefore, closer targets see higher directional probabilities as hypothetical spheres reduce in surface area. For accurate calculations of downward-impinging releases, conservative flame envelope and thermal contour dimensions are extracted from release orientations above the horizontal plane. The ignited event frequency associated with a given QRA inventory is modified by the directional impact probability for each event. Cumulative frequencies are calculated by summing the total frequency of individual flame or thermal contour events impacting a given point in 3D space, as illustrated in Figure 3.

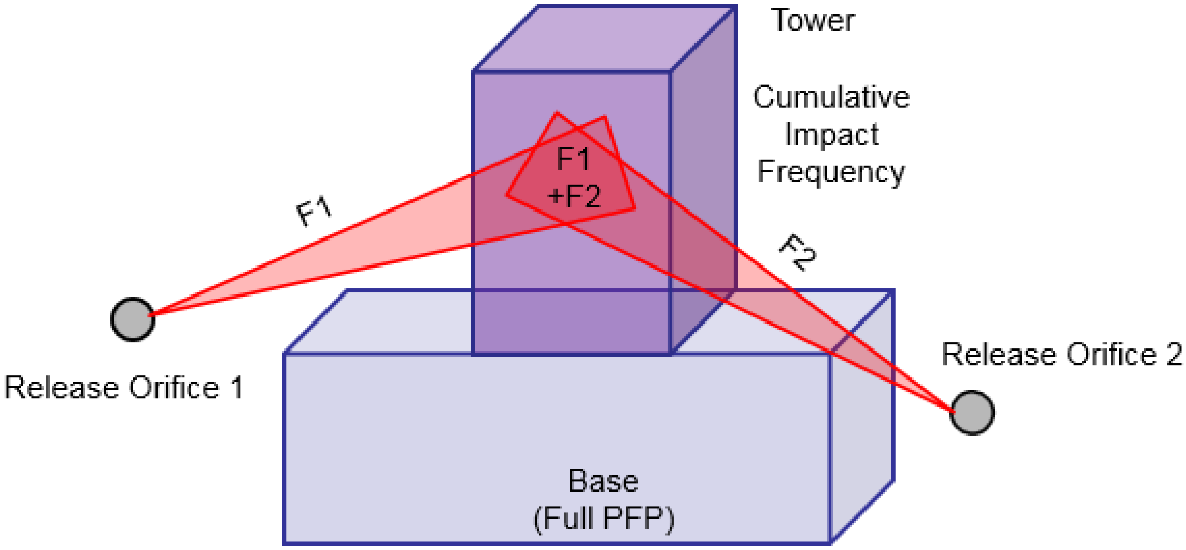


Figure 3. Individual and Cumulative Impact Frequency Concept

Thermal Capacity Exceedance

The frequency of exceeding the structural survivability criteria (i.e. capacity of the structure to maintain integrity for a given radiation intensity and duration) can now be calculated for all points in the fire zone. Durations of all QRA inventories are retrieved and paired with their corresponding impact event frequency. The cumulative frequency of all events where the structural capacity has exceeded is calculated and overlaid on the impingement exceedance map for the whole facility. This information is then used according to flowchart in Figure 1 as input to the non-linear structural analysis. Annual exceedance frequency criteria intended for application towards aggregated risk criteria are used to evaluate the safety level under the accidental fire event. This analysis ultimately demonstrates risk to the structure and provides recommendations for design and optimization of PFP scheme.

Structural Fire Response Analysis

For understanding the structural response of individual members and the entire structural system, a series of fire response analyses are performed. In the structural fire response analysis, PFP requirements, and structural integrity of the steel structures and safety critical piping, valves, equipment and E&I systems under accidental fire conditions are considered. As a result of the risk-based fire durations and specific spatial fire threatened locations from the impingement exceedance maps, necessary PFP scheme for the structure and SCEs are determined.

3. Case Studies

Field Application: Fire Integrity of Steel Structures for Risk-based Fire Scenarios

Process safety studies for typical onshore oil and gas facilities were carried out to optimize initial PFP schemes by adopting the risk-based FIA as described in the previous section. The studies included QRA for the entire plant, fire integrity analyses, and PFP optimization for process modules, equipment and piperacks.

Risk-based fire duration calculations were performed for assessment and optimization of PFP during the QRA and probabilistic FRA. Release locations and directions were considered for calculation of risk-based jet fires impinging on certain process area. Calculations were performed for grade level and at several elevations for areas with large vertical equipment. In-house developed tools were used for calculations to determine the fire durations for cumulative frequencies reaching an exceedance frequency criterion of 10^{-5}/year. This approach resulted in calculation of more realistic jet fire durations based on leak frequencies, directionality of a jet and process conditions, release rate, and pressure (see Figure 4)

With the calculated risk-based fire durations per the exceedance frequency criterion, ductility level analyses were performed using ABAQUS software package [19]. The analyses included structural members and process safety critical equipment and piping systems. Large equipment (e.g. large bore piping, process vessels, ESD valves and actuators) were also included in the FE Model as shown in Figure 5. These detailed models enabled capturing the interaction between process safety critical systems and the supporting structure.

Structures were evaluated using jet flame impingement at 300 kW/m^2 for duration corresponding to fire impact exceedance frequencies less than or equal to 10^{-5}. Flame impingement of this manner may cause failure of unprotected steel structures within short order. Heat-up curves of members were developed using detailed transient heat transfer analyses for typical members. Since the objective of this study was to obtain an optimized scheme to ensure the integrity of support structures, piping, and pressure vessels, the adequacy of PFP scheme was checked by comparing the calculated plastic strains with allowable limits per FABIG [5]. Similarly, the failure of structural members was evaluated based on UKOOA recommended performance criteria [26]. This study also examines thermal radiation exposure of entire structure due to 150 kW/m^2 near field jet fire radiation for its corresponding duration. These radiation values were chosen for evaluation to ensure structural integrity and to prevent escalation of fire hazard [1].

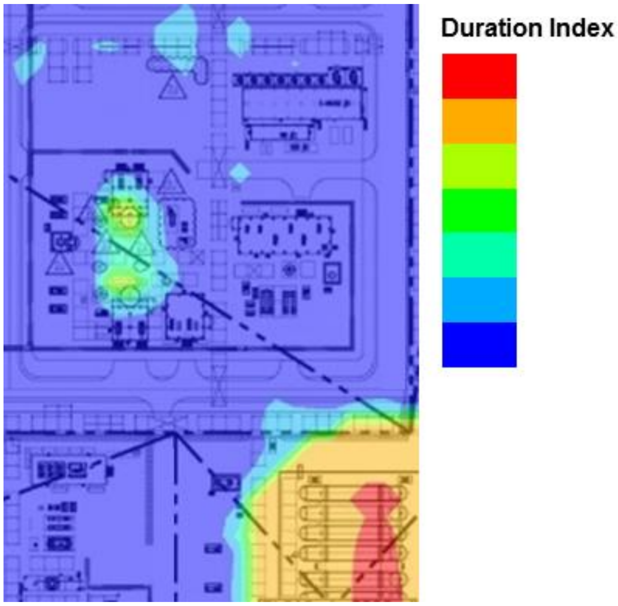


Figure 4. Impairment Duration Map for Jet Fire Impingement per 10^{-5} Annum for the Facility

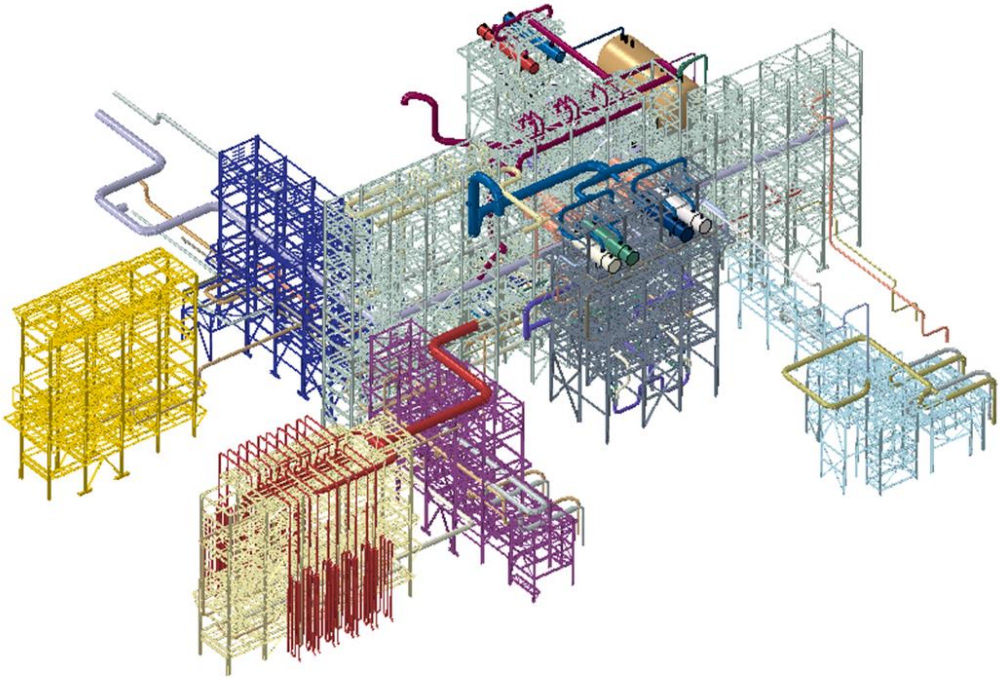


Figure 5. Finite Element Model with Large Equipment and Piping for PFP Optimization

The optimized PFP scheme depends on assessment approach; i.e., deterministic or performance-based approach. The reductions in PFP area are presented in Table 1 and Table 2. Using the performance-based approach, a further reduction of 20 to 30% in PFP coating areas of typical large process modules were achieved compared to the PFP schemes generated using prescriptive approach (Table 1). A maximum PFP reduction of 60% was attained for a typical piperack module (Table 2). This was accomplished by analyzing the entire processing unit in its entirety and by strategically protecting critical components such that the stability of supported piping is maintained.

Table 1 Comparison of Required PFP Areas for a Large Process Module

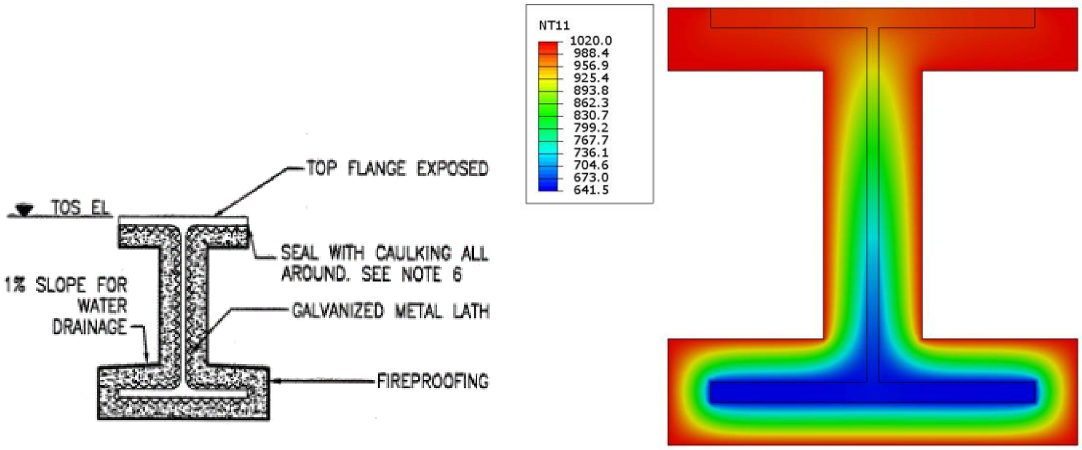
Description	**PFP Scheme Approach**	**Total Surface Area(m^2)**	**PFP Surface Area (m^2)**	**% PFP Reduction with respect to Prescriptive**
Typical Equipment Structure	Prescriptive	11000	7000	-
	Deterministic		5400	23%
	Risk Based		4700	33%

Table 2 Comparison of Required PFP Areas for a Typical Piperack

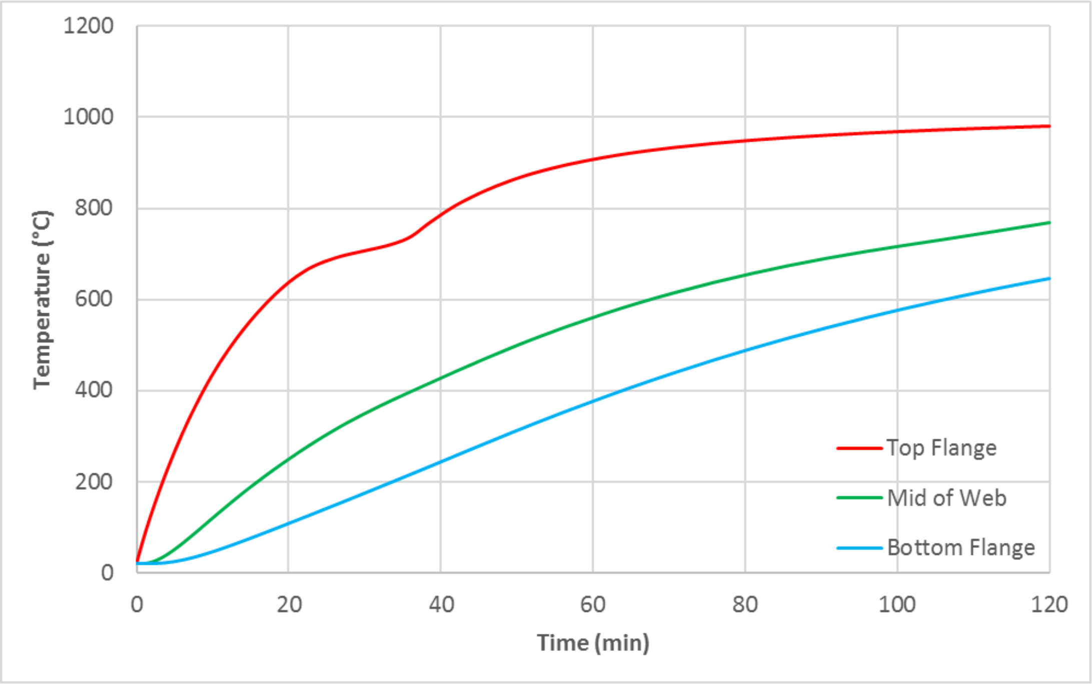
Description	**PFP Scheme Approach**	**Total Surface Area(m^2)**	**PFP Surface Area (m^2)**	**% PFP Reduction with respect to Prescriptive**
Typical Piperack	Risk Based	1900	810	57%

Fire Response Analysis for Exposed Top Flange Cases

Although API [27] allows the top flange exposed PFP application for horizontal beams, the effect of the partial PFP application should be fully understood with regards to jet fire risks. API 2218 does not account for jet fire cases and targets protection against pool fire where radiation from grade limits the heating of top flange due to not having line of sight. However, at facilities susceptible to jet fire, exposed top flanges can significantly lower the fire endurance limits. Case studies with partial PFP application for horizontal beams were carried out. Figure 6 shows an example of partial PFP application, i.e. top flange exposed beam section. With considerable temperature gradient over the top flange exposed beam subjected to a jet fire scenario, the partial PFP application was found to cause the section stiffness and capacity to decrease. Three cases of PFP application were investigated for load-bearing capacity comparison: beam with fully covered PFP, and top flange partially exposed and top flange completely exposed beams (Figure 7). The beam with top flange fully exposed resulted in reduction in both stiffness and capacity, i.e., 60% and 40% remaining, respectively. Although it may not be practical to apply PFP to top flanges on most places due to presence of piping and grating, reduced capacity of beams should be taken into account when jet fire risks are credible.

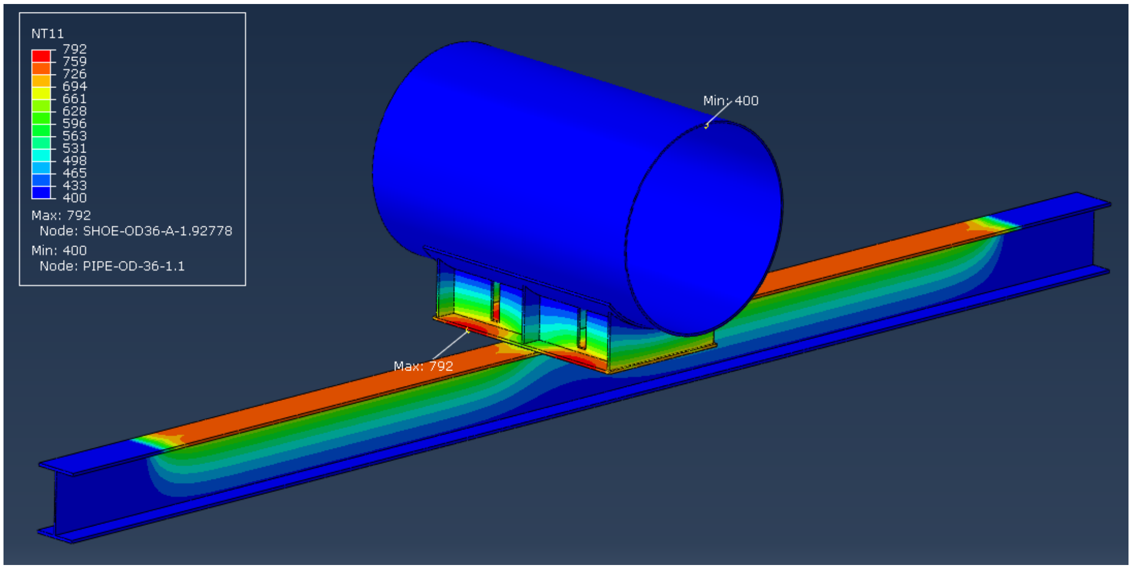


(a) Temperature Gradient for Typical Top Flange Exposed Beam Section

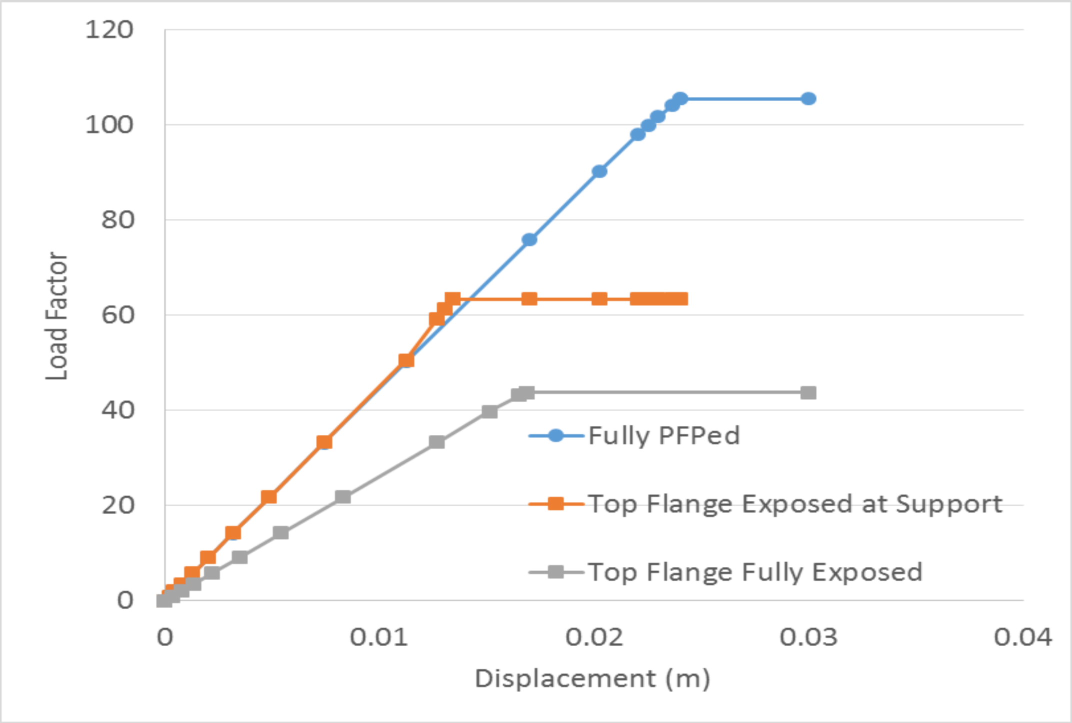


(b) Temperature Heat-up Curves Across Depth of Top Flange Exposed Beam

Figure 6. Typical Heat Transfer Analysis Results of Top Flange Exposed Beam Subjected to 150kW/m^2 Radiation: (a) Temperature Gradient, and (b) Different Temperature Heat-up Profiles



(a) 3D Heat Transfer Analysis Results for Top Flange Exposed Beam and PFP Applied Pipe



(b) Ultimate Strength Comparison between Fully and Partially Protected Beams

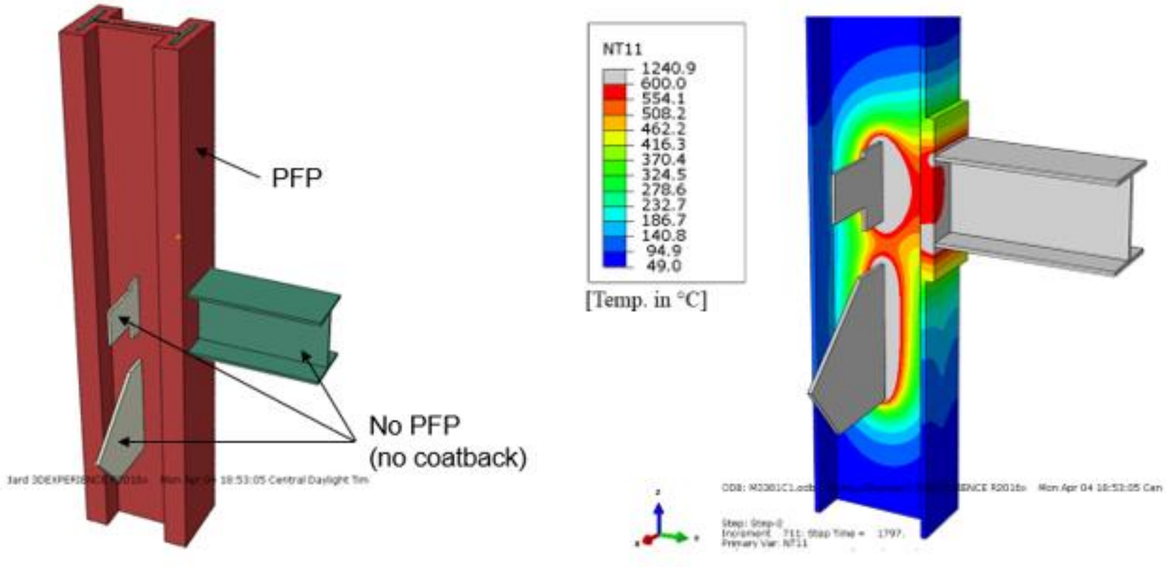
Figure 7. Capacity Degradation of Top Flange Exposed Beam Subjected to a Jet Fire Scenario

PFP Coatback Requirement Assessment

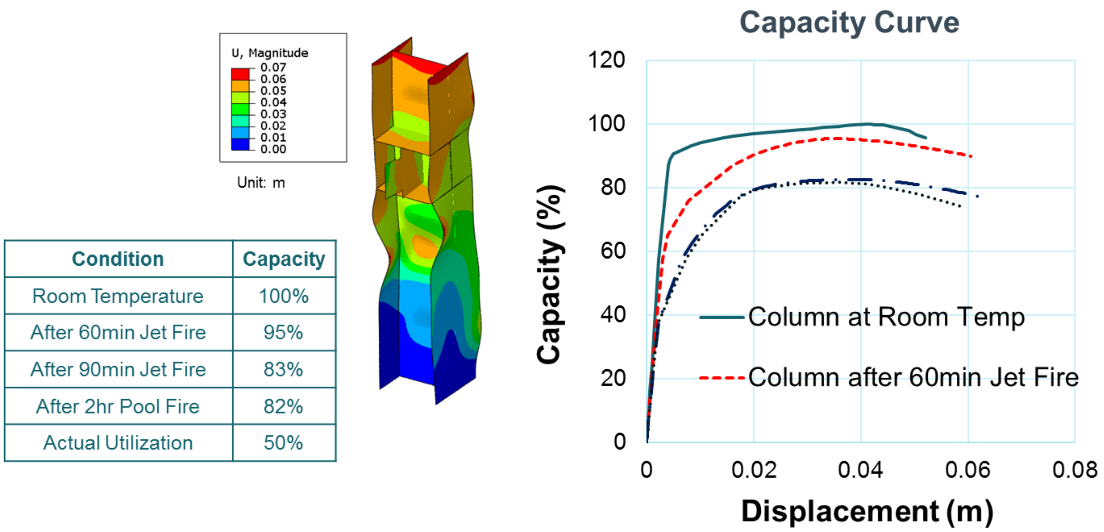
For the purpose of reducing the heat conduction into a protected steel element supplied from a physically attached unprotected steel element, a typical mitigation for steel connections is PFP coatback application. PFP is coated back from a protected steel element to limit the extent and severity of “hot spots” developing in the protected member at the region of the connection. The added PFP on the otherwise unprotected member, limits the distance between the connection and the surface directly exposed to fire. API [2] prescriptively specifies the PFP coatback length for exposed steel supports to be a minimum of 300 mm, and a range of 400 to 600 mm for the PFP coatback length is typically practiced for offshore structures [28].

The PFP coatback requirements for typical connections were also investigated using risk-based fire scenarios for onshore and offshore projects supported by the authors. The influence of PFP coatback was assessed for thermal response and the structural integrity of the selected connections. Based on the performance-based coatback analyses for typical steel connections of structures, necessity of PFP coatback at the steel connections between protected and unprotected members was evaluated.

Detailed three-dimensional (3D) FEA models were developed for typical connections. A typical connection is shown in Figure 8-a. Transient heat transfer analyses followed by non-linear strength analysis for a given fire scenario was conducted using ABAQUS software package [19]. In the non-linear strength analysis, the load-bearing capacities of the critical connections were assessed using temperatures obtained from the heat transfer analyses. The analysis results (Figure 8-b and c) were reviewed and compared with fire event locations/durations to optimize the PFP coatback requirements. Based on the coatback analyses with risk-based approach the required PFP coatback lengths were reduced to 200 mm or completely removed for cases with a relatively thick PFP material applied to the protected element.



(a) FE Model for PFP'd Steel Connection (b) Temperature Results for Strength Analysis



Condition	Capacity
Room Temperature	100%
After 60min Jet Fire	95%
After 90min Jet Fire	83%
After 2hr Pool Fire	82%
Actual Utilization	50%

(c) Ultimate Capacity Pushdown Analysis of Steel Column without Coatback Application on Framing Members

Figure 8. Performance-based FIA for Steel Connections and Coatback Analysis: (a) FEA Model (b) Temperature Distribution from Thermal Analysis, and (c) Ultimate Capacity Assessment

Fire Protection of Equipment and Piping

Safety critical equipment and piping systems within the fire zones were identified using hazard assessments to prevent escalation and facilitate the emergency operations. Although nominal amount of fireproofing materials is required for the equipment and piping systems, the protection scheme is usually determined and applied by the fireproofing material suppliers. Verification of the adequacy of heat transfer characteristics, e.g., number of layers, installation configurations, and thicknesses, allows for PFP optimization for these systems without compromising from safety. In this study, performance-based FIA with deterministic fire scenario generation approach were considered for the verification of the PFP applications for the safety critical equipment and piping. For some cases heat conservation and fireproofing requirements were both met through engineered insulation solutions. Additionally, details along termination points and transitions were checked using analytical methods calibrated with respect actual fire test results.

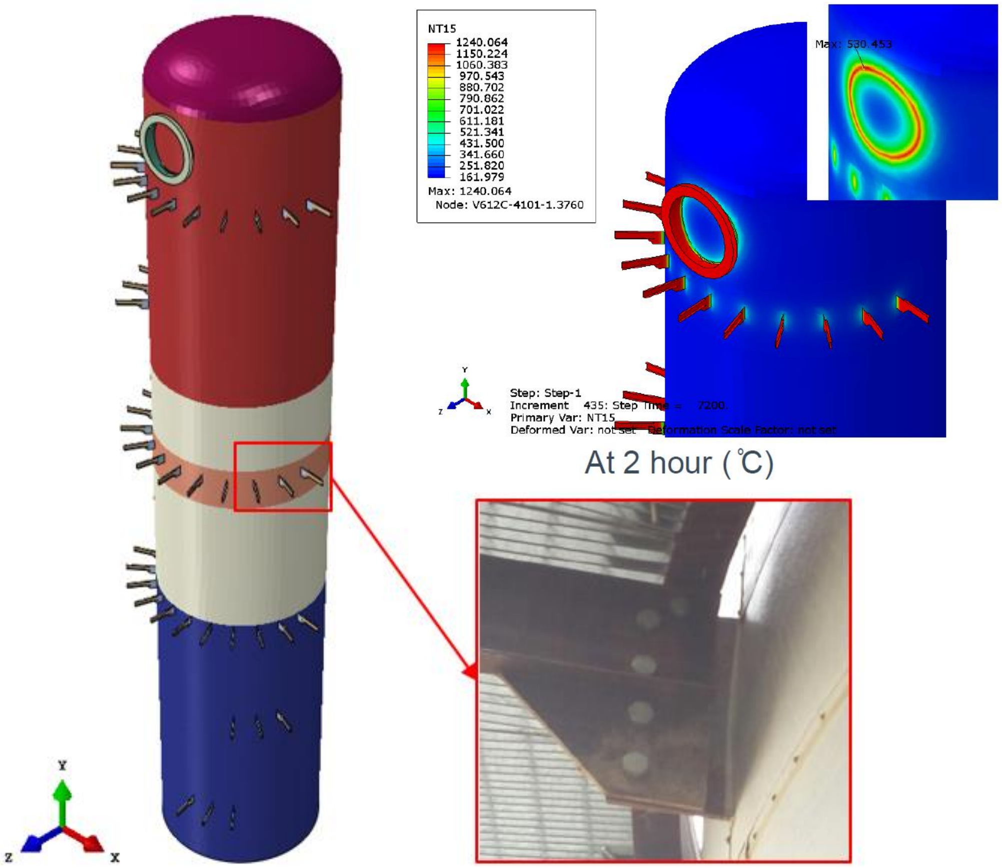
Fireproofing of the process equipment such as pressure vessels and vessel attachments were investigated using refined FE Models of the large process vessels. 3D transient hear transfer analyses were performed using ABAQUS software [19] for the local FE models that consist of pressure vessel shell, fireproofing material on the vessel shell, and the exposed attachments as illustrated in Figure 9. Temperatures at the outer surface of the protected shell were generally limited to 400˚C. Considering strength reduction of the steel material at elevated temperatures [3, 18], the coatback requirements for the exposed attachments were evaluated. In addition, Boiling Liquid Expanding Vapor Explosion (BLEVE) risk for the pressure vessel at elevated temperature was assessed using HYSYS dynamic process simulations and FEA based rupture analysis [29].

Fire Protection of Electrical Systems

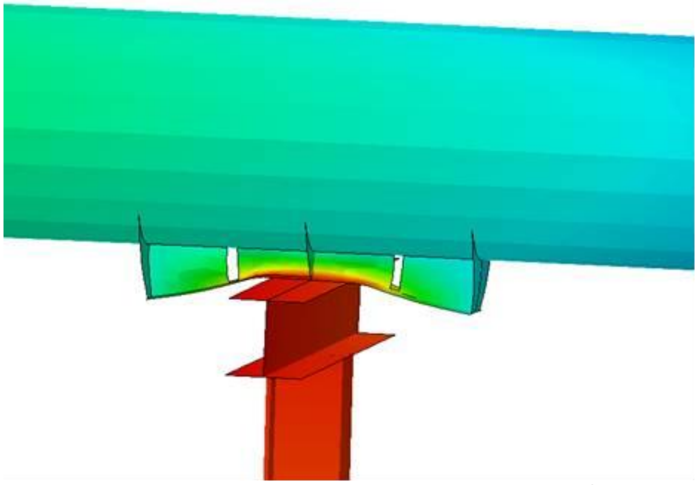
Electrical and Instrument (E&I) systems, which are required to remain functional up to a specified fire duration in order to control critical operations, should also be classified as safety critical systems. These safety critical E&I systems usually include electrical and instrument cables and trays, process shutdown/de-pressurization valves, control systems, etc. The E&I systems are, in general, protected with jet fire rated fireproofing materials that can be flexible jacket type with stainless steel/mesh cladding or endothermic material PFP [2].

For safety critical E&I systems, 3D FEA models were developed using ABAQUS [19] as shown in Figure 10. For the FIA, thermal properties of PFP materials were obtained from parametric calibrations with fire test data of the fireproofing materials vendors provided. In order to evaluate the thermal response and PFP requirements for various E&I systems, transient heat transfer analysis was performed. Deterministic fire scenarios were utilized in the analysis, and the maximum allowable fire durations for different number of PFP configurations were assessed. Residual strength assessment of cable trays and supports were performed at elevated temperatures by utilizing thermal response results from the heat transfer analyses.

Unprotected sacrificial cable tray supports can conduct heat to the protected cable tray through the contact area between exposed cable tray support and protected cable tray. This may lead to localized high temperature in cable trays and cables. To investigate the length of required coatback, 3D transient heat transfer analyses were also conducted. The inner surface temperature of cable tray, obtained from heat transfer analysis, was used as input for a 2D FE Analysis to evaluate the cable temperature under accidental fire events.

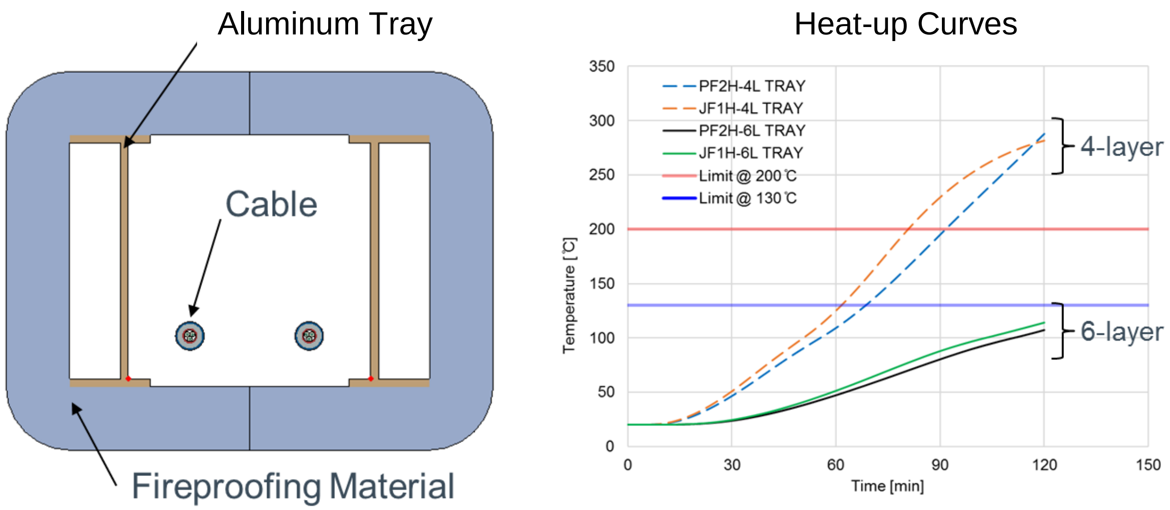


(a) Transient Heat Transfer Analysis for Pressure Vessel Attachment Coatback

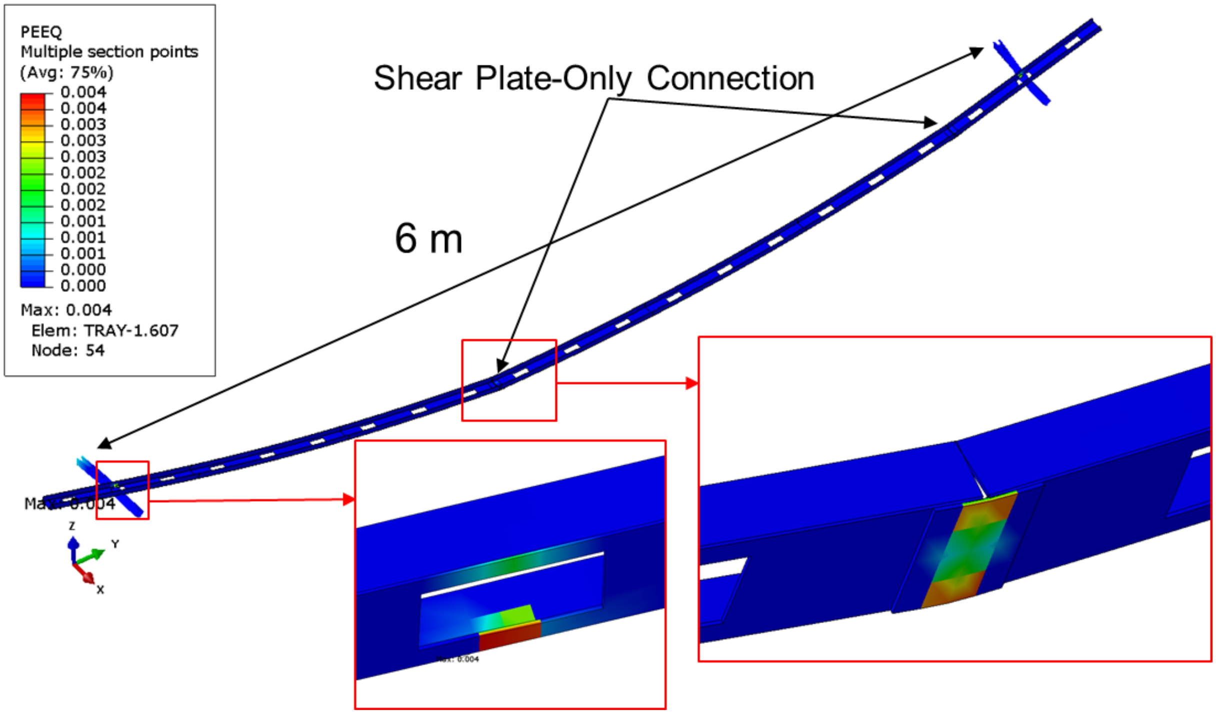


(b) Pipe-Shoe Permanent Deformation after 2 Hours 300 kW/m^2 Jet Fire Impingement through Exposed Portion of Pipe Shoe

Figure 9. Local FIA for PFP Optimization of Critical Equipment and Piping Systems: (a) Transient Heat Transfer Analysis for Pressure Vessel Attachment Coatback, and (b) Thermal-Strength Interaction Analysis for Piping and Pipe Supports with PFP



(a) Transient Heat Transfer Analyses for Cable Trays



(b) Ductility Level Fire Response Analysis for Protected Cable Trays

Figure 10. E&I Cable Tray FIA for PFP Optimization: (a) Transient Heat Transfer Analyses, and (b) Ductility Level Analysis

4. Conclusions

Various regulatory bodies require Oil & Gas production and processing facilities for an explicit identification, risk assessment, and mitigation solution to be prepared for fire hazards. QRA techniques are now increasingly used for the assessment of fire hazards at facility, and for the effective planning of remedial measures. The use of deterministic fire scenario is prevalent in industrial practice to develop required PFP scheme for protection against fire. Although deterministic approach yields a reduced fire protection requirement, there is still a room for further optimization of PFP application while properly identifying the safety critical aspects. In this paper, we have presented a PFP optimization methodology by adopting a holistic multi-disciplinary approach to achieve a performance-based PFP scheme balancing the hazard control and risk mitigation.

For a complete FIA, non-linear thermal-structural analyses for all typical modules / structures of the facility are performed. All safety critical equipment and piping along with any neighboring structure are included in the FE Models. The temperature time history is obtained by a separate heat transfer analysis for both protected and unprotected members individually, which is later utilized in the stress analysis for the performance assessment and PFP optimization. Through case study, we demonstrated that performance-based optimization approach resulted in 20 to 60% reduction in PFP requirements from that suggested by using prescriptive approach for typical modules. In addition, coatback requirements, top flange protection, fireproofing of E&I systems, pipe supports, vessels, valves, etc. can also be optimized by adopting a performance-based approach. Coatback and top flange fire protection requirements can be critical for structure susceptible to relatively long duration pool fires and jet fires.

Since it is not feasible to test all possible PFP configurations for all sections or process components at a plant, understanding and interpretation of fire tests plays a critical role in extrapolating test results through analytical methods. The parameters used as the inputs for FE Models shown in this study were calibrated and checked against test data. High fidelity simulation methods discussed in this paper resulted in better understanding of risk and more accurate calculation of fire response for a range of components protected with different types of PFP.

The main advantages of reducing application of PFP coating on non-critical members are cost savings and integrity management improvements during life cycle of a facility. Considering the fact that CAPEX and integrity management are major concerns for most structures at petrochemical facilities, optimization of PFP for plant structures has significant benefits for operators and owners of onshore and offshore assets without compromising the risk targets. The integrated structural, foundation and equipment and piping systems fire analysis approach presented in this study is considered to be a significant addition to state of the art in fire protection design of petrochemical facilities. Improvements in analysis and design methods are expected to result in better selection and engineered application of PFP at the critical locations only without compromising from safety requirements. This also ensures that safety critical elements are protected against credible hydrocarbon fire scenarios.

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