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Evaluating the Transient Radiant Heat Flux Impacts to Occupied Buildings

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Abstract

Traditional methods of evaluating radiant heat impacts on occupied buildings typically rely on a threshold radiant heat flux value to evaluate occupant vulnerability. While this is acceptable within the methodology of fire hazard evaluation presented in the API RP 752 standard, the approach does not account for structure properties, the transient nature of the fire, or duration of exposure. These factors are an important part of describing the potential impact on occupied buildings, as well as the vulnerability of the building's occupants. Because API RP 752 does not provide any specific guidance on these topics, the specific evaluation of a building and its response to thermal radiation is left to the analyst. Previous work applied first principle numerical tools to define the impacts from continuous external fires. This paper continues that work to evaluate transient thermal loading on the building exterior and heat transfer through the building materials to better determine building occupant vulnerability. This work will help to define the limits of radiant heat dose for occupied buildings that may be exposed to external fires.

INTRODUCTION

Protection of plant personnel for facility siting purposes is typically addressed through the application of the American Petroleum Institute (API) recommended practice (RP) 752[1], which is primarily focused on the location and vulnerability of occupied buildings. These buildings, where personnel carry out their duties, are assumed (within the context of API RP 752) to provide some protection from accidents that may occur at the facility. However, the potential effects on personnel in buildings are highly dependent on the way the equipment and processes are laid out within the facility, the type of building construction, and the distribution of buildings within the plant boundaries, specifically their proximity to hazardous chemicals at the plant.

An analysis conducted to satisfy API RP 752 generally should include three classes of hazards:

- Explosion overpressure or blast wave exposure
- Fire radiation exposure, including pool fires, jet fires, and exposure to an ignited flammable vapor cloud (flash fire)
- Toxic gas exposure

The focus of this work is specifically addressed towards exposure to fire radiation from continuous fires whose radiant impact changes over time (a transient heat flux).

BUILDING SITING

The methodology and tools available for safety siting studies are generally well known within the process safety community. The methodology can be structured as a staged process that allows the study to stop at multiple points when the analysis shows that the impacts, or risk, to the subject population (building occupants) is found to be tolerable. These methodologies have been summarized in several published papers[2] [3].

The specifics of radiative loading on buildings has been addressed by various international agencies[4] [5] [6]. In these publications, the vulnerability of building occupants was estimated using a fixed value of thermal radiation (e.g., 35 kW/m^2) without any mention of the duration of exposure.

FIRE RADIATION IMPACTS

Occupied buildings can be impacted by many forms of fire radiation including:

- Fireballs due to instantaneous releases of flammable fluids, including boiling liquid expanding vapor explosions (BLEVEs)
- Vapor cloud fires (flash fires) due to a release that forms a flammable vapor cloud
- Jet (torch) fires due to continuous, pressurized releases of flammable fluids
- Pool fires due to pooled releases of flammable liquids

Of these fire types, jet fires and pool fires are typically the dominant types considered as a threat within a building siting study. Buildings within a vapor cloud fire are typically not exposed long enough to ignite the building, even if it is constructed of flammable materials. Fireballs, in addition to their short duration, are historically rare events and are typically not considered a credible threat to occupied buildings. It is the long duration jet and pool fires that pose a threat to buildings through flame contact or high levels of thermal radiation.

The vulnerability of building occupants to fire radiation is certainly mitigated by the building being a physical barrier to the direct effects of fire radiation. However, there are several concerns for the building itself that affect occupant vulnerability:

- Building materials that are combustible could be ignited if the radiative flux and exposure duration are sufficient;

- The integrity of non-combustible materials can be compromised due to degradation or deformation following exposure to radiative heat flux for a sufficient exposure time, resulting in building collapse; or,
- The increased temperature of the building shell exposed to thermal radiation results in a significantly increased interior temperature.

In all cases of exposure to thermal radiation, the magnitude of the radiative flux and the duration of exposure are equally important variables. The principle behind this, whether the exposure is burns to a person's skin, ignition of wood, or weakening of structural steel, is the temperature rise that occurs.

The exposure of occupied buildings to high levels of fire radiation, such that it could adversely affect the building occupants, is the focus of this analysis, including the complex techniques required to evaluate building impacts due to fire radiation, such that the impacts to occupants can be evaluated. The precursor to this work[7] began addressing the issue of radiative loading to occupied buildings by evaluating a section of a typical pre-engineered metal building (PEMB) during external thermal radiation loading with durations up to an hour. The findings of that work included:

- Steady-state conditions were observed in the structural steel within about 10 minutes for the scenarios modeled.
- Insulated PEMBs may suffer damage to the exterior panels, but are not expected to experience any structural degradation under long-duration exposure to radiant loading up to 100 kW/m^2.
- Uninsulated PEMBs exposed to radiant heat fluxes greater than 35 kW/m^2 may experience a loss of structural integrity within about 5 minutes of exposure, such that building occupants could be threatened.
- Structural members in uninsulated PEMBs can reach temperatures that may be capable of igniting flammable materials in the interior of a building.

CONTINUING STUDY

To further evaluate the potential impacts to PEMBs, and thus the vulnerability of building occupants, this work sought to further investigate the potential impacts of transient heat flux loadings on a subject building.

Accidental Fire Loading

In order to study transient heat flux loadings, a dynamic system that is often found in process facilities was modeled to better represent realistic plant hazards. For this reason the modeling package CANARY by Quest® was used to calculate the transient release rate and the transient release conditions accounting for the thermodynamics of the releasing system. In addition, CANARY by Quest® was used to model the thermal radiation from transient jet fires.

The characteristic jet fires were modeled based on a release from a propane storage vessel. The vessel is used to store propane as a liquid, at atmospheric temperature and elevated pressure.

A two-inch hole is assumed to occur in the piping connected to the liquid side of the storage vessel. Within seconds, the release is ignited and forms a jet fire. The release flow rate drops quickly in the first two minutes as the system depressurizes. The rate continues to drop and at 28 minutes the flow rate reaches a value that is half of the initial flow rate. As the flow rate and pressure drop the jet fire shrinks in size, and the thermal radiation impacts shrink accordingly.

Figure 1 shows the thermal radiation at four separate points near the jet fire. The position of these four points are static relative to the release point (storage vessel). Not all points near the jet fire experience the same reduction in thermal radiation as the flame shrinks. As the jet fire shrinks the reduction in length is greater than the reduction in diameter or lateral dimensions. Thus, the points near the end of the initial flame will experience a larger drop in radiation than near the source of the jet fire.

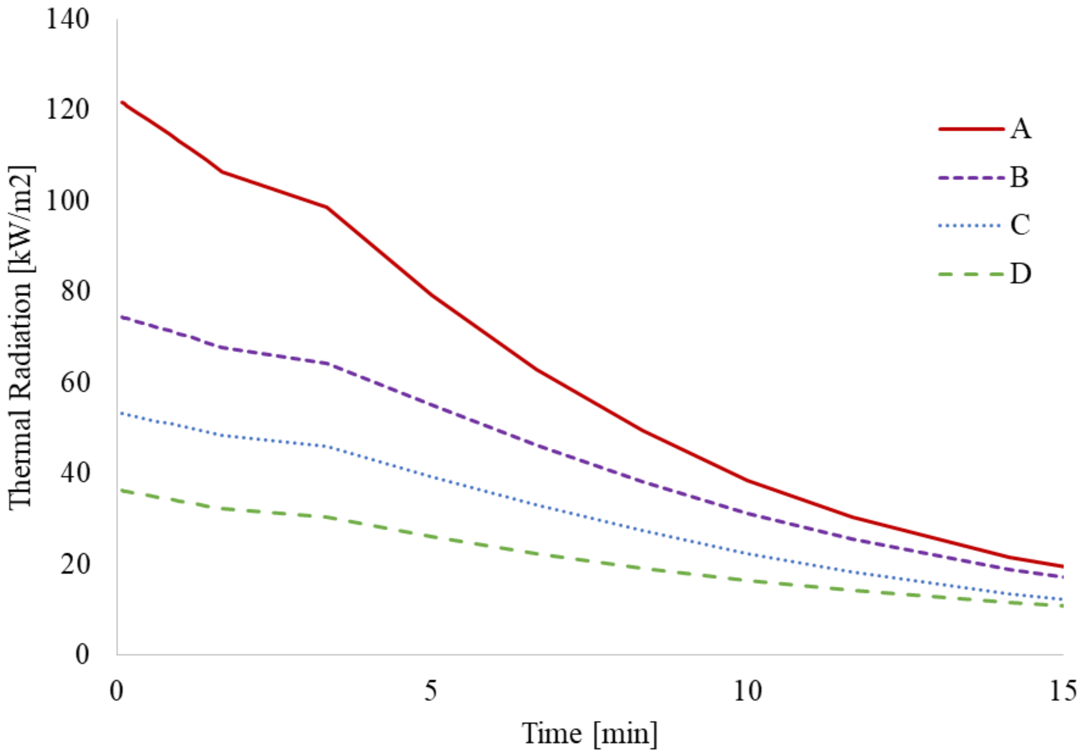


Figure 1. Transient Radiation Load Cases A-D

Complex Analysis

The potential impacts from fire radiation described above were investigated using the numerical heat transfer tools contained in a finite element analysis (FEA) model. Based on the FEA results, the temperature rise in construction materials exposed to an external fire can be estimated. Resulting temperatures can be used to determine the potential for ignition of construction materials, integrity loss of exterior construction elements, and integrity loss of the main structural framing members.

The performance of a typical PEMB exposed to transient thermal radiation loading external to the building is evaluated in this study. In the scope of this paper it is assumed that the fire event happens outside the building, exposing the building wall to a heat flux. The vertical cladding of such buildings would typically be constructed of exterior corrugated metal panels screwed to horizontal girts that span approximately 20 feet between columns. Depending on the building, insulation may be installed between panels and the building frame. This analysis will address both insulated and uninsulated structures, and it is assumed that a large portion of the exterior surface of the building wall is exposed to these heat fluxes.

Calculation Methodology

Heat flux from the fire flows from outside to inside the building wall. Due to the high temperature of the flame, radiation dominates the heat flow from the fire to the exterior surface facing the fire. Re-radiation of the exterior surfaces is also considered. External convective effects are ignored for this analysis due to the dominance of radiative heat transfer. At the exposed surface, heat is transferred through the solids by conduction. The interior surfaces, not exposed directly to fire radiation, release heat through radiation and convection to the surrounding interior air at low temperature (initially at ambient temperature). The air medium inside and outside the PEMB cladded wall are not explicitly modeled in the FEA.

To model heat radiation, for each radiative heat flux scenario, the methodology presented in the predecessor paper (reference 7) was applied. In each case, the equivalent incident thermal radiation equal to the values presented in Figure 1, varying with time, were applied to the external surface.

Conduction of heat through the solid body of the wall (construction material) results in a temperature change of the wall. The conduction equation is used within the FEA software to calculate the temperature change, where conduction depends on the specific heat, density, and most importantly, thermal conductivity, of the materials in the wall structure.

Once the temperature of the interior surface of the PEMB wall rises above its initial temperature, heat flows to the interior space through radiation and convection. Depending on how hot the wall materials get, internal heat flux may be dominated by radiation or convection. Since the air inside and outside the PEMB wall are not explicitly modeled, an assumption for the building internal temperature must be made, as well as emissivity of the internal surface and convection coefficient of the inside air.

Calculation Model

The PEMB wall considered in this study includes 26 gauge vertical spanning metal R-panels (structural panels used primarily for PEMBs roof and wall construction) screwed to horizontal 8x25z16 girts at 4 feet on center vertically. For the purpose of this paper, only a 2-foot by 4-foot area of the wall is modeled. Wall insulation is also modeled and it is assumed that the compressed thickness of the insulation at the girt location is ¾ inch, and elsewhere is a full 3 inches. It is assumed that the panel is screwed to the girt with #10 screws at every foot, and the equivalent area of the screws are included in the model. The Abaqus FEA software[8] was used to perform the heat transfer analysis. Geometry of the model is shown in Figure 2. More specifically, 8-node linear heat transfer brick elements are used to mesh the geometry.

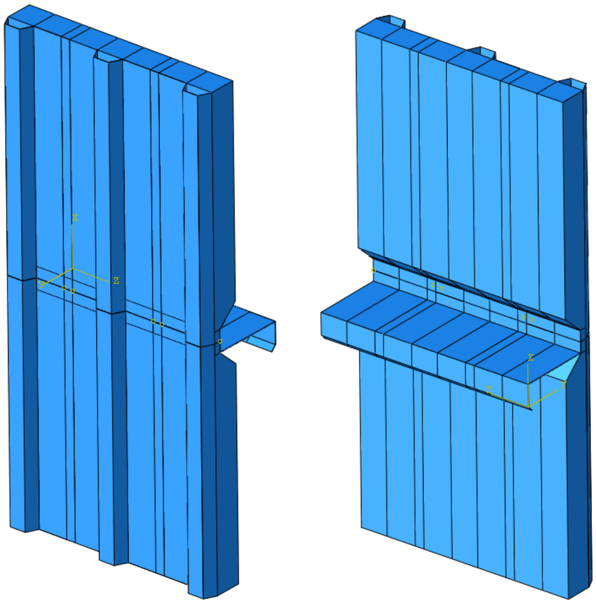


Figure 2. Geometry of the Modeled Portion of the PEMB Wall (Exterior and Interior, with Insulation)

Based on several manufacturers' available data, an R-value of R-10 was used for the 3-inch thick insulation. Squeezed insulation at the girt location is assumed to have R-value of R-5. Temperature dependent thermal material properties are used based on Eurocode 4[9] specifications. For all heat flux scenarios, the exterior face of the wall panel was exposed to heat flux for a duration of greater than 15 minutes according to the transient heat flux curves presented in Figure 1.

Overall, 5 different cases are defined. One case is a wall structure with insulation exposed to thermal load A at the exterior surface, and exposed to 25°C room temperature at the interior surface. Four other cases include a wall structure *without* insulation exposed to thermal loads A-D at the exterior surface, and exposed to 25°C room temperature at the interior surface.

STUDY RESULTS

The results of the simulations show the transient temperature variation in the modeled portion of the wall exposed to a range of transient heat fluxes. The results of an insulated wall exposed to thermal load A is shown in Figure 3. For comparison, a wall without any insulation with exposure to 50 kW/m^2 after 2 hours is shown in Figure 4. The uninsulated wall shows considerably higher girt flange temperatures.

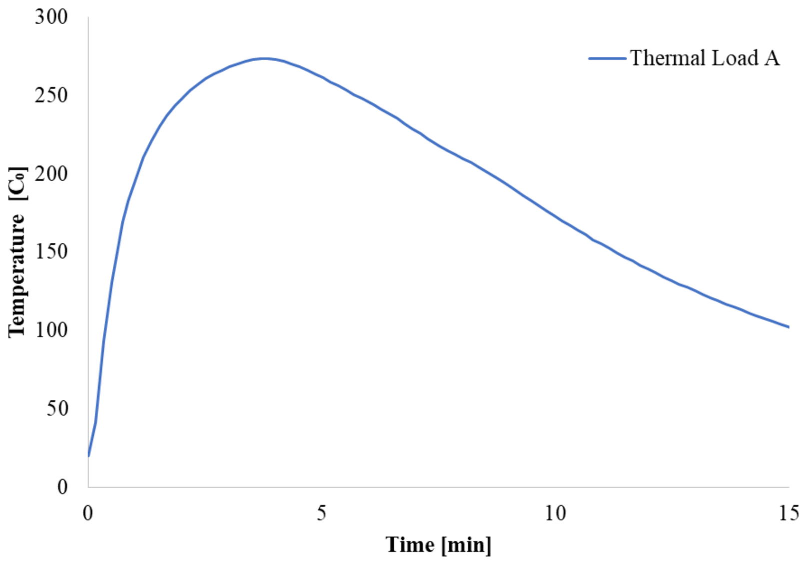


Figure 3. Temperature Variation at the Hottest Point of the Girt for a PEMB Wall *with* Insulation

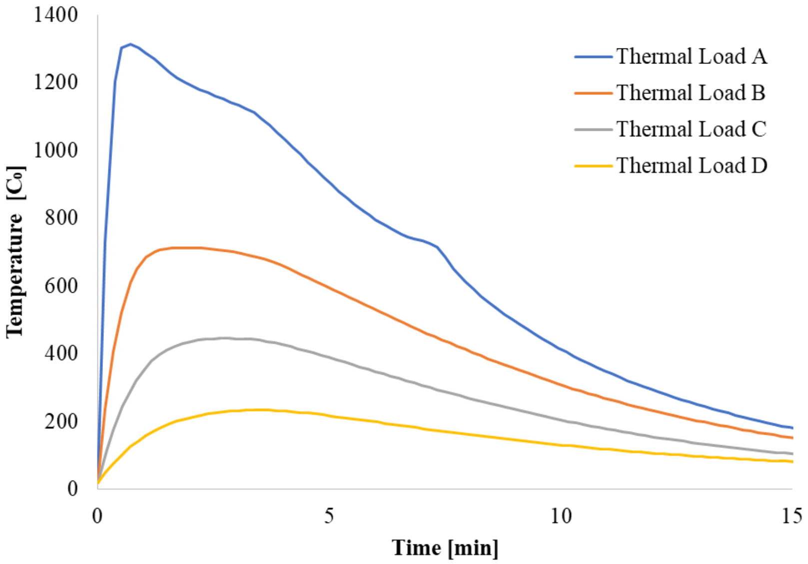
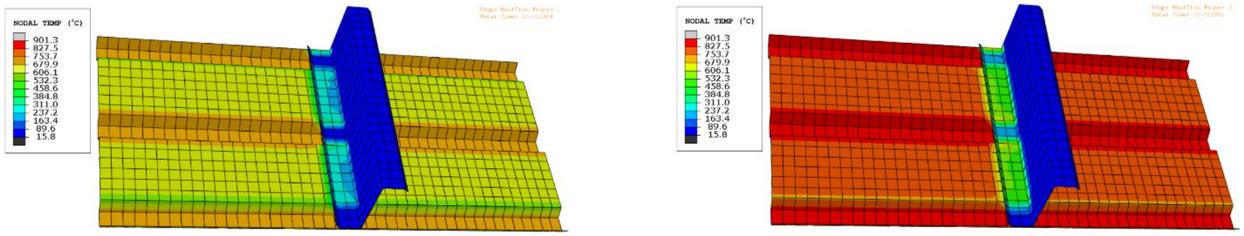
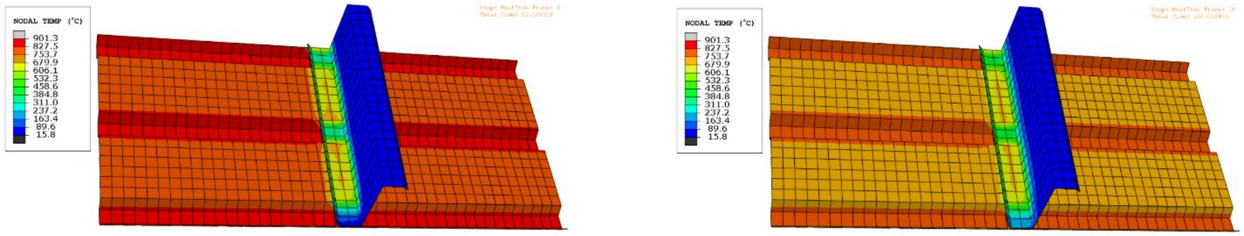


Figure 4. Temperature Variation at the Hottest Point of the Girt for a Wall *without* Insulation for Varying Transient Heat Flux Loads

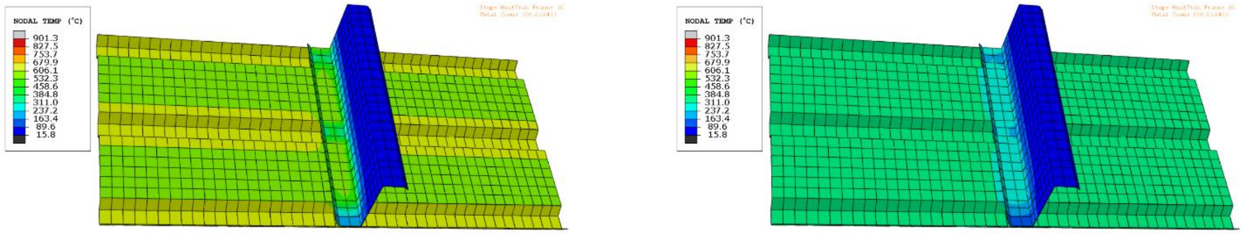
Variation of temperature in the PEMB wall is plotted in Figure 5 for the uninsulated case, at six different times, for the Thermal Load B case.



(a) 10 seconds (b) 30 seconds



(c) 60 seconds (d) 180 seconds



(e) 300 seconds (f) 600 seconds

Figure 5. Temperature-time History of PEMB Wall Segment – Transient Loading B

To evaluate the effects of temperature on the steel structural members of a building, it is helpful to understand how the properties of steel change as temperature rises. The reduction factors presented in Table 1 (below) provide an indication of how the stress-strain relationship changes when the steel structural members heat up, based on the Eurocode 4 publication[6]. For example, at 600°C, the steel's modulus of elasticity is 31% of the modulus of elasticity at the standard temperature (20°C). Likewise, the steel's yield strength is 47% of the yield strength at standard temperature (20°C). Ultimate strength of the steel is approximately 25% higher than the yielding stress at temperatures below 400°C. At temperatures above 400°C, steel loses its hardening capacity. Ultimate strength and yielding stress of steel have essentially the same values at these temperatures.

Table 1. Reduction Factors of Steel Stress-Strain Relationship Parameters at Different Temperatures Based on Eurocode 4

T (°C)	Young's Modulus Reduction Factor	Yielding Stress Reduction Factor	Ultimate Strength Reduction Factor
20	1	1	1.25
100	1	1	1.25
200	0.9	1	1.25
300	0.8	1	1.25
400	0.7	1	1
500	0.6	0.78	0.78
600	0.31	0.47	0.47
700	0.13	0.23	0.23
800	0.09	0.11	0.11
900	0.0675	0.06	0.06
1,000	0.045	0.04	0.04

FINDINGS

Based on the analysis results provided above, the following conclusions and observations are drawn:

- When insulation is present, a transient heat flux peaking above 120 kW/m^2 (thermal load A) results in a maximum temperature of around 275°C, at the hottest location of the girt. At this temperature, the girt strength is not reduced structurally, although the girt stiffness may be reduced by 10-20%. Therefore, it could also be assumed that the integrity of the vertical columns and the frame would not be compromised.
- If insulation is <u>not</u> installed on a PEMB, a transient heat flux peaking above 50 kW/m^2 (thermal load C) results in a maximum temperature of around 450°C, at the hottest location of the girt. At this temperature, around 20% of the steel strength is lost, and around 35% of the girt's stiffness is compromised. The structural integrity is expected to be intact for typical structural loading. Therefore, it could also be assumed that the integrity of the vertical columns and the frame would not be compromised. A similar results are found with an uninsulated building with thermal load D.
- If insulation is not installed on a PEMB, temperatures exceeding 700°C in the girt may be reached for transient heat fluxes exceeding 70 kW/m^2 (thermal loads A and B). At 700°C, around 75% of the steel strength is lost, and around 85% of the girt's stiffness is compromised. Structural integrity is compromised for most structural loadings.
- For the uninsulated case, there is significant variance for the final girt temperatures from one level of fire heat flux to another. For all considered fire heat flux cases, since both the wall panels and the structural members radiate heat toward the building interior, there will be a potential for high heat fluxes to impact building occupants. The authors recommend

performing computational fluid dynamic analysis, explicitly modeling the interior air, to further investigate the non-insulated case to quantify the potential impact on building occupants.

Some further observations, based on the expected building response are:

- Insulated buildings may suffer damage to the exterior panels, but are not expected to experience any structural degradation, given the transient loadings presented in this paper. Therefore, building occupants are not vulnerable to structural collapse given the external heat flux examples evaluated here.
- Uninsulated PEMBs exposed to transient radiant heat fluxes beginning at greater than about 60 kW/m^2 may experience a loss of structural integrity depending on the specific transient load. Static loads at this level (even those that are sustained for greater than about 3 minutes) are sufficient to induce a loss of structural integrity in the element, such that building collapse is possible.
- Structural members in uninsulated PEMBs can reach temperatures that may be capable of igniting flammable materials in the interior of a building. Further investigation into the temperatures reached by exposed surfaces of structural members and additional factors that influence the transfer of heat to interior elements is warranted.

The previous work (reference 7) found that under static loading, the building structural elements reached a steady-state temperature in less than five minutes. In this work, the peak temperature is reached in less than five minutes due to the transient loading patterns that were applied. These transient loading patterns are considered typical for jet fires following accidental release from hydrocarbon systems. Consequently, the building structural response is expected to be known within about 5 minutes from the beginning of the fire radiation exposure.

Finally, for both insulated and uninsulated PEMBs, the exterior paneling reaches temperatures where failures may be likely. While it is not well understood how a failure may manifest, failure of exterior panels have the potential to allow exposure of the building's interior elements. Consequently, this is another area for further investigation.

SUMMARY

Based on the analysis presented in this paper, the differences in insulated and non-insulated PEMBs are found to be significant. Insulated PEMBs provide a higher level of protection to structural elements as opposed to uninsulated PEMBs. Insulated buildings should be able to withstand thermal radiation greater than 100 kW/m^2 in both static and transient loading without suffering structural degradation. While an uninsulated building exposed to static radiant flux loadings greater than 35 kW/m^2 may have structural steel elements that reach temperatures exceeding 400°C, transient loadings of the type evaluated in this paper can reach up to 60 kW/m^2 before the same effects are realized. Above these values (35 kW/m^2 static loading and 60 kW/m^2 for a transient peak) significant damage to the building structure could occur, and structural failure may be possible.

Further building analysis, using computational fluid dynamic analysis and explicit modeling of the interior space, is recommended to better describe occupant vulnerabilities. For both insulated and uninsulated PEMBs, the potential failure modes of the exterior paneling requires further investigation to ensure that such failures would not result in exposure of the interior space to radiation.

Given that the building's structural response can be known within about 5 minutes of the beginning of a fire, something resembling a dose-response relationship can begin to be formed from these results. However, more investigation and calculations must be done before this relationship can be quantified.

REFERENCES

[1] API (2009). *Management of Hazards Associated with Location of Process Plant Permanent Buildings*. API Recommended Practice 752, American Petroleum Institute, 1220 L Street, Northwest, Washington, D.C. 20005, Third Edition, December 2009.

[2] Marx, J. D., and Ishii, B. R. (2016), *A Comprehensive Approach to API RP 752 and 753 Building Siting Studies*, Journal of Loss Prevention in Process Industries, Volume 44, November 2016, pages 748-754.

[3] Cornwell, J. B., and Ishii, B. R. (2018), *What API RP 752 Does Not Tell You – But People Will Ask*, Presented at the 14th Annual Global Congress on Process Safety, Orlando, FL, April 2018.

[4] Technica, Ltd. (1988). *Techniques for Assessing Industrial Hazards*. World Bank technical paper number 55, prepared by Technica, Ltd., London, England, 1988.

[5] TNO (1989), *Methods for the Determination of Possible Damage to People and Objects Resulting from Releases of Hazardous Materials* (the Green Book). The Netherlands Organization of Applied Scientific Research, Voorburg, The Netherlands, December, 1989.

[6] TNO (2005), *Guidelines for Quantitative Risk Assessment* (the Purple Book). CPR 18E, the Netherlands Organization for Applied Scientific Research, Committee for the Prevention of Disasters, The Hague, Netherlands, 2005.

[7] Marx, et. al. (2018), *Radiant Heat Flux Impact Criteria for API RP 752 Building Siting Studies*, Presented at the 14th Annual Global Congress on Process Safety, Orlando, FL, April 2018.

[8] Abaqus (2014). Abaqus Unified FEA, Version 6.14, Dassault Systèmes, 2014.

[9] Eurocode 4 (2005). Eurocode 4: Design of Composite Steel and Concrete Structures – Part 1-2: General Rules - Structural Fire Design, BS EN 1994-1-2: 2005, British Standards Institute, 2005.