Risk-Based Approach – Facility Siting Addressing Fires Impacting Process Plant Permanent and Portable Buildings

Combining Exceedance Curves and Human Vulnerability Criteria

An ioMosaic White Paper

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Abstract

This manuscript describes a risk-based approach with the aim to identify which occupied buildings in a process facility could be impacted by thermal radiation due to fires. This approach complies with API Recommended Practice 752 and 753 criteria and it consists of the following two steps: (1) risk-based quantitative assessment and (2) exceedance curve development. Additionally, a sensitivity analysis for risk reduction measures is evaluated. A case study is developed for illustrative purposes and the results confirm the following approach capabilities and characteristics: (a) a risk-based approach is considered the foundation for developing exceedance curves, (b) exceedance curves are a good engineering tool for identifying which occupied buildings comply or do not comply with given tolerability risk criteria; and (c) sensitivity analysis of outcomes associated with high risk levels impacting affected buildings is an effective and inexpensive approach for defining and comparing suitable and cost-effective risk reductions measures during the decision-making process.

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Introduction

The approach described in this manuscript focuses on the impact Loss of Containment scenarios (LOCs) of flammable materials that could lead to fires to portable and permanent buildings. Fire outcomes are based on the source term models which consider released material properties and behavior, conditions of the release and various phenomena that accompany the release of hazardous materials under such conditions (e.g., expansion, choked flow, two-phase flow, aerosolization, rainout, etc.) **[1]**. These models are important because they provide input data to the fire models and the accuracy from the fire models is dependent upon the accuracy in the source term computation. Despite the large number of possible fire events, few categories of industrial fires are relevant for facility siting leading to occupant fatalities located inside a building; i.e., jet fires, pool and tank fires, fireballs and flash fires **[2]**.

During the development of the risk-based quantitative assessment, it is critical to properly locate all the structures/buildings present in a hazardous site **[3]**. All identified LOCs **[4]** are analyzed and modeled following the criteria established in references **[5]**, **[6]**, **[7]**, **[8]**, **[9]** and **[10]**. Note that these cited references provide the basis for risk-based quantitative assessment development, which is the basis of the proposed approach **[11]**. In this manuscript, a risk-based approach focused on identifying which occupied buildings in a process facility could be impacted by thermal radiation due to fires is defined and characterized. The building occupant vulnerability is determined based on several thresholds later illustrated on the manuscript. Finally, when no potential fire scenarios which could adversely affect the target building are identified, it is justified that no further analysis is required.

Based on API Recommended Practices 752 **[12]** and 753 **[13]**, a risk-based facility siting assessment may be expressed as numerical values of individual risk, aggregate risk, or exceedance values. They can also be expressed as graphical formats which include cumulative frequency versus consequence curves, or matrices with numerical axes. The proposed risk-based approach combines exceedance curves **[3]** with worldwide recognized thermal radiation thresholds **[14]** with the aim to identify which buildings are affected at a cumulative frequency of interest by high thermal radiation thresholds and it is required to propose mitigation measures intended to reduce the risk.

Note that another approach to identify areas impacted by high values of thermal radiation at a cumulative frequency of interest would be the development of thermal risk contours evaluated at a different heat flux or heat dose thresholds. While this is considered as the first step to identify affected areas, it is important to understand that the risk contours are not dedicated to a specific location and the approach proposed in this paper is more accurate as it addresses specific locations in a hazardous facility. As a result, the development of thermal risk contours and dedicated exceedance curves are considered to completely address facility siting for fires.

Exceedance Curves Development

A risk-based quantitative assessment development allows acquiring knowledge on all the fires outcomes which impact a given location of interest; e.g., manned building. A valid tool for managing and interpreting all this information is the exceedance curve. The exceedance curve approach was developed following the issue of the 2003 version of the Chemical Industries Association (CIA) guidance **[10]** and is widely used for characterizing facilities. Exceedance curves can be used as a probabilistic description of the potential for a target location to experience various levels of effects; i.e., heat radiation from fires.

An exceedance curve relates the cumulative frequency of occurrence of any given parameter being exceeded; e.g., heat flow received by fires, overpressure received by explosions and concentration/dose received by toxic dispersions. When addressing fires, the exceedance curves are called Heat Flow Exceedance Curves (HFECs). The construction of an HFEC is based on identifying all fires that impact a given location under analysis and sorts the values of each heat flow in descending order. The consequence modeling of fire-related outcomes must be conducted by different heat flux thresholds of interest; i.e., as more thresholds evaluated, the more accurate the exceedance curve will be. The steps required to construct a HFEC are explained in reference **[3]**. HFECs can be applied for identifying and selecting which buildings/structures require a more detailed analysis or which should be included in the mitigation plan if these do not meet specific criteria. Specific criteria for facility siting studies addressing buildings impacted by fires are described in **[3]**. It is important to mention that based on the criteria used for facility siting, if the exceedance heat flow level is lower than the minimum exceedance heat flux threshold value evaluated, it is confirmed that the building is in a tolerable risk region. Otherwise, the building/structure is identified to be impacted by fire events at a cumulative frequency greater than the facility siting tolerability criteria and as a result, further analysis needs to be performed; i.e., mitigation measures to reduce the risk to a tolerable limit.

Table 01 lists the key results obtained from a risk-based quantitative assessment: cumulative frequency of occurrence at a given exceedance heat flux selected value, exceedance heat flux value and total number of fire outcomes that impact the location under analysis at the evaluated exceedance heat flux value. Note that as said above, as more heat flux thresholds defined in the thermal radiation damage criteria for consequence modeling, the more detailed information is available for the facility siting analysis. Based on the results listed in **Table 01** below, the construction of an HFEC to identify whether a building is impacted at a cumulative frequency of interest is impacted or not. Note that this approach can be performed for all the building/structures defined in the complete facility siting analysis.

Table 01: Fires Impacting a Given Building Location

Heat Flux [kW·m^{-2}]	Cumulative Frequency [yr^{-1}]	Outcomes [-]
5.00	8.28E-05	229
10.0	7.15E-05	204
12.5	2.06E-05	172
15.0	1.73E-05	145
25.0	1.60E-05	136
35.0	1.46E-05	115
40.0	1.41E-05	98
50.0	9.03E-06	67
65.0	7.98E-06	51
75.0	5.89E-06	43
85.0	5.45E-06	34
100	5.05E-06	22

From **Table 01** it can be observed that 229 fires are identified to impact the building under analysis. While this value can seem to be huge, it is a reasonable value based on accounting for all LOCs that could generate a potential fire when a facility handling hazardous materials is analyzed. From these 229 fires, 22 of them impact the process equipment at heat flux value of 100 kW·m^{-2}, 34 fires (the 22 fires that impact the building at 100 kW·m^{-2} plus 12 fires that impact at 85.0 kW·m^{-2}) and so on.

The individual frequency of occurrence of each of the 229 fires is available for later usage. As a result, it becomes evident that accurately estimating the likelihood of occurrence of all LOCs is a very important step to accurately predict which buildings are impacted by fires at a cumulative frequency of interest. Detailed information on how to estimate the frequency of occurrence of a LOC can be found in reference **[15]**.

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Case Study

The following case study is intended to illustrate the process on how to identify potential locations affected by fires at a cumulative frequency threshold of interest. Before conducting facility siting to address fires, a detailed risk-based quantitative assessment is performed and both individual (i.e., risk contours) and societal (FN Curves) risks are estimated. Additionally, thermal risk contours are developed at given heat flux value for fire zone identification and emergency-planning purposes **[11]**. Based on the thermal risk contours results, areas within the hazardous facility are identified to be affected by thermal radiation. Thus, it is decided to conduct a detailed facility siting study for identifying which occupied buildings inside these areas are identified to be affected at a cumulative frequency of interest. While references **[8]** and **[16]** describe how occupied buildings were analyzed due to explosions impacts and toxic and flammable dispersions, the following study focuses only on pool fires outcomes; i.e., fire assessment.

All pool fire outcomes impacting occupied buildings under analysis were identified, filtered and collected from LOCs identified in ALL process units within a process facility that could release hazardous materials or energy **[17]**. Each associated individual frequency of occurrence was estimated and impact distances predicted at different selected heat flow values of interest were modeled by using SuperChems™ **[18]**.

Heat Flow Exceedance Curves (HFECs) are developed for six (6) occupied buildings located in an area susceptible to be impacted for pool fire outcomes (see Figure 01) based on the thermal radiation risk contours. A target frequency of occurrence of 1.00E-04 yr-1 was the given threshold for identifying target buildings potentially impacted by pool fires based on CIA criteria [10]. The heat flow exceedance threshold defined in this case study is based on criteria established in BEVI **[19]**; i.e., 35 $kW \cdot m^{-2}$. BEVI **[19]** considers that people located inside a building are protected from heat radiation until the building catches fire. The threshold for the ignition of buildings is set at 35 $kW \cdot m^{-2}$. If the building is set on fire, a probability of fatality of 1.00 is assumed if the heat radiation exceeds 35 $kW \cdot m^{-2}$ and if lower, no fatalities are considered.

Based on **Figure 01**, it can be observed that only **BUILDING-01** was identified to be affected by a higher heat flow than 35 $kW \cdot m^{-2}$ at the given frequency threshold (1.00 E-04 yr^{-1}); i.e., estimated heat flow: **40 $kW \cdot m^{-2}$**.

Based on the criteria selected **[10]** and **[19]**, it can be concluded that **BUILDING-01** is considered to not be a tolerable region. It is proposed to further study which potential risk reduction measures could minimize the actual risk and therefore ensure the integrity of the building and the safety of its occupants without re-locating or reinforcing the building. The following section describes the *Sensitivity Analysis for Risk Reduction Measures Definition* approach.

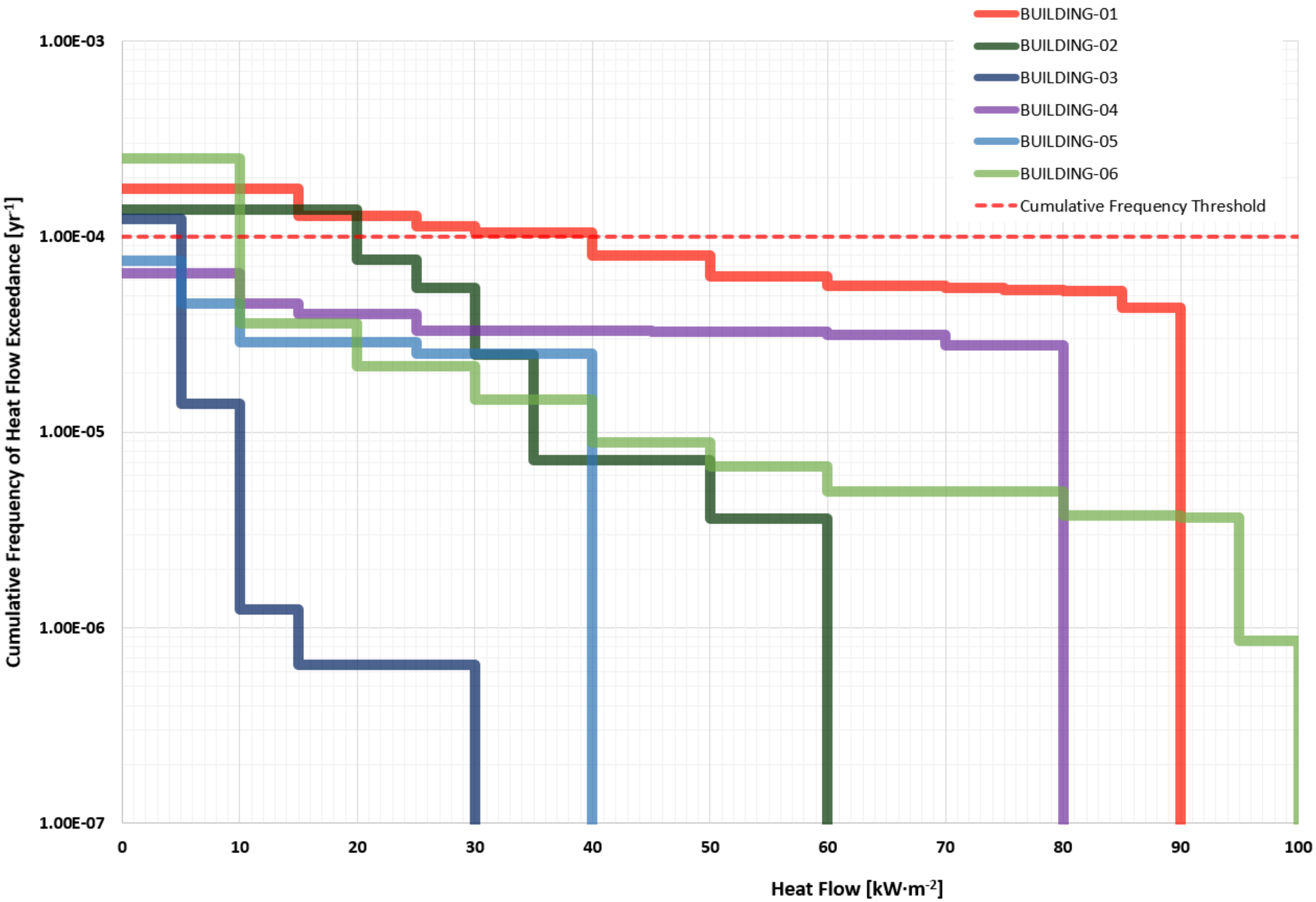

Figure 01: Heat Flow Exceedance Curves for Six (6) Selected Occupied Buildings – Pool Fires

Sensitivity Analysis for Risk Reduction Measures Definition

Risk reduction can be achieved by implementing prevention measures (i.e., intended to reduce the frequency of occurrence of LOCs), and/or mitigation measures (i.e., intended to reduce the impacts of LOCs). API RP 752 **[12]** lists risk reduction measures based on the decreasing reliability and are categorized by type. **Table 02** lists the API RP 752 **[12]** hierarchy of mitigation measures applicable to reduce the risk of potential fires.

Table 02: Process Equipment and Scenario Definition

Risk Reduction Measure	Description
Passive	**Action**
Eliminate hazard	Substitute with nonhazardous material/process conditions
Prevent release	Upgrade metallurgy or design of equipment
	Reduce leak sources
	Rate equipment for maximum upset pressure
Control size of scenario	Utilize spill control dikes, curbs
	Minimize release rate
	Reduce inventory of hazardous material
Mitigate effect to building occupants	Relocate not essential personnel
	Design or upgrade existing building
Active	**Action**
Prevent release	Safety Instrumented Systems (SIS)
Control size of scenario	Fire and gas/emergency shutdown systems (FGS)
Mitigate effect to building occupants	Issue occupants with personal protective equipment (PPE)
Procedural	**Action**
Prevent release	Mechanical integrity inspection
	Permits for hot work, lockout/tagout, line breaking, lifting, etc.
Control size of scenario	Manual active firefighting systems
Mitigate effect to building occupants	Emergency response plan
	Evacuate occupants during start-up and planned shutdowns

As part of the sensitivity analysis, it is important to mention that good engineering tools should be provided for decision-making when a building is included in the mitigation plan. SuperChems™ **[18]** has the capability to provide detailed results and information after HFEC construction. These results allow the user to identify which are the most suitable and cost-effective risk measures to be implemented for risk reduction and are based on the following of steps:

- Identification of ALL fire outcomes that impact the building under analysis. **Table 03** is an example of the key information that SuperChems™ **[18]** collects per each outcome impacting on the target location under analysis.

- Ranking of ALL outcomes by sorting the individual frequencies of occurrence in descending order: this step allows to identify the outcomes with highest frequencies of occurrence. The first key outcomes identified in this list have the potential to be addressed for prevention measures; i.e., reduction of frequency of occurrence.
- Ranking of ALL outcomes by sorting exceedance heat flux values impacting the building in descending order. This step allows to identify the outcomes with highest impacts to the target building. The first key outcomes identified in this list have the potential to be addressed for mitigation measures; i.e., reduction of impacts.

Based on this information, key fire outcomes (i.e., reducing frequency of occurrence and reducing heat fluxes) can be identified. An iterative procedure calculation is conducted with the aim to calculate new values that would satisfy compliance with facility siting criteria as illustrated above. After the selected safeguard is implemented and the results are calculated, a new HFCE is constructed to graphically observe whether the prevention and/or mitigation measures are effective enough. Thus, a new table (see **Table 04**) lists the key fire outcomes modified and new values of frequency of occurrence and heat radiation is developed. This analysis allows to identify the gap between original and the pursued risk levels, which define the risk reduction level to be achieved when considering process safeguards to be implemented.

Table 03: Information of Most Contributing Outcomes to Target Building

Fire	Coordinates	Equipment	Leak size [in]	Frequency [yr^{-1}]	Heat Flow [$kW{\cdot}m^{-2}$]
01	X_1, Y_1, Z_1	Pipe P-F01	LS_{01}	F_{01}	EHF_{01}
02	X_1, Y_1, Z_1	Vessel V-F02	LS_{02}	F_{02}	EHF_{02}
03	X_1, Y_1, Z_1	Flange F-F03	LS_{03}	F_{03}	EHF_{03}
…	…	…	…	…	…
n	X_n, Y_n, Z_n	Pump PF-n	LS_n	F_n	EHF_n

Table 04: Predicted Values of Most Contributing Outcomes Ensuring Risk Compliance

Fire	New Individual Frequency [yr^{-1}]	New Heat Flow [$kW{\cdot}m^{-2}$]
01	NF_{01}	$NEHF_{01}$
02	NF_{02}	$NEHF_{02}$
03	NF_{03}	$NEHF_{03}$
…	…	…
n	NF_n	$NEHF_n$

The definition of potential process risk measures to be implemented is a procedure to be brainstormed and agreed with client, for example:

- Prevention measures intended to reduce the frequency; e.g., SIS, FGS
- Mitigation measures intended to reduce exceedance flow; e.g., dike, restrictive orifice

If the prevention/mitigation measures proposed result to be either non-effective or impractical to be installed, recommendations should be implemented directly to the building properties; e.g., relocation, reinforcement, etc., to ensure that the building complies with the selected facility siting tolerability criteria.

Following the case study illustrated in **Figure 01**, a sensitivity analysis is performed by accounting for the most contributing outcomes impacting **BUILDING-01**; i.e., five different outcomes are analyzed. The analysis highlighted that reduction of the heat flow from pool fire due to LOCs from piece of Equipment 01 (P-XX-YY-001, i.e., process pipe) would be effective for risk reduction. After a more in-depth review of the input data, it is found that the LOC is in an unconfined area and potential for confinement construction is confirmed. Other fires from LOCs are in the same area and are also identified to be contributor outcomes to the target building. Thus, confinement construction in the mentioned area decreases the impacts of the Equipment-01 and other process equipment impacted the building/structure under analysis.

As part of the sensitivity analysis, iterative calculations are conducted by varying the size of confinement with the aim to ensure which length and width of confinement construction would satisfy facility siting criteria. Finally, a new HFEC is constructed and it can be observed that the proposed safeguard is effective as **BUILDING-01** is no longer impacted by a heat flux of **35 $kW \cdot m^{-2}$** or higher at a cumulative frequency of 1.00E-04 yr^{-1} (see **Figure 02**). Based on **Figure 02**, after the safeguard is implemented, **BUILDING-01** is affected by a heat flux of **25 $kW \cdot m^{-2}$** and according to the selected risk criteria, no further actions are required to decrease the risk level in the structure under analysis.

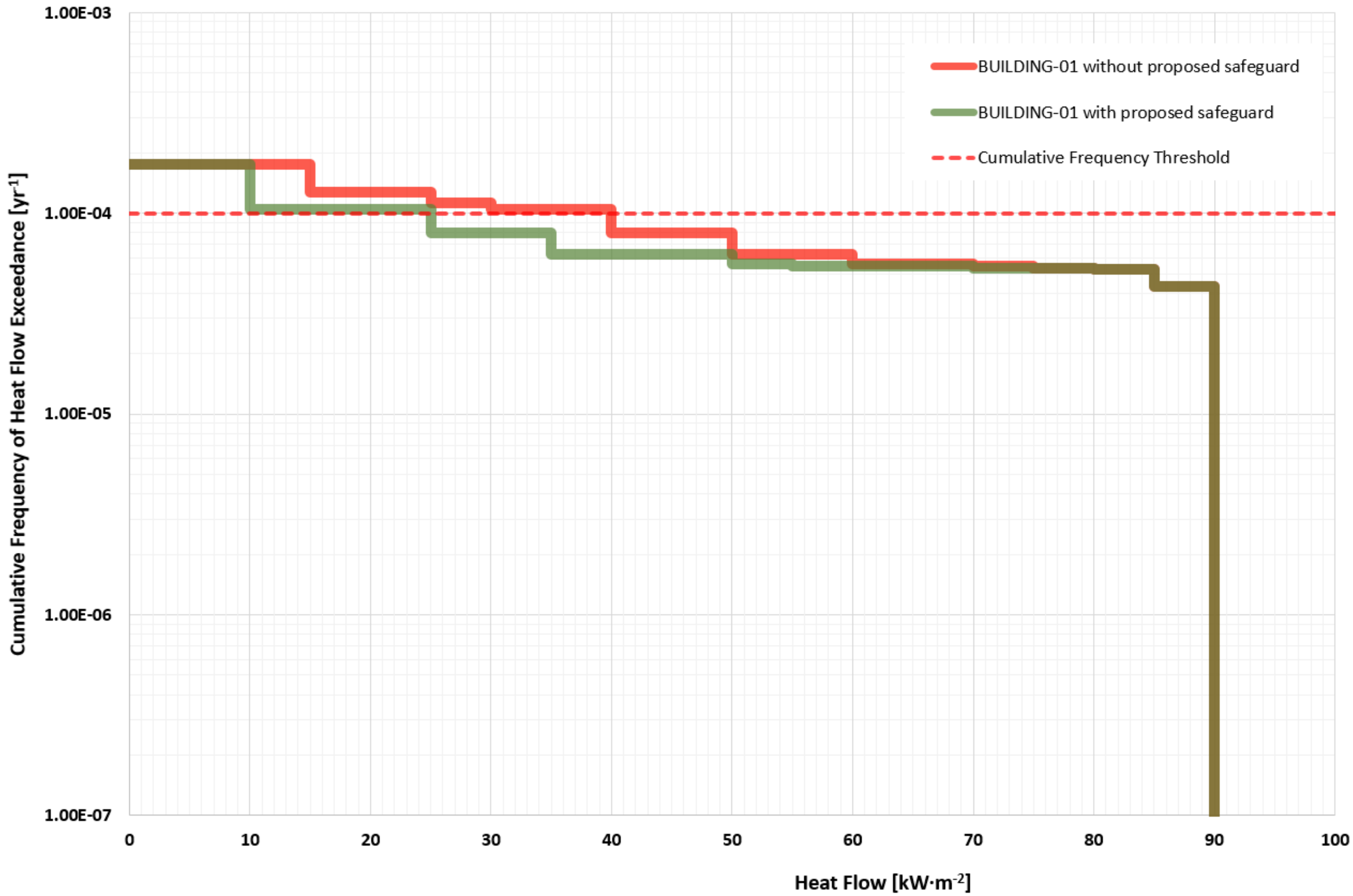

Figure 02: Heat Flux Exceedance Curves for BUILDING-01 With and Without Proposed Safeguard

Conclusions

Thermal risk contours are useful to identify areas where portable or permanent process plant buildings can be affected by thermal radiation outcomes at high cumulative frequencies. However, HFECs can be used for the specific identification of occupied buildings that may be impacted by heat flux values received from industrial fires. Filtering all outcomes that entail the same fire classification (e.g., pool fires), dedicated HFECs can be constructed per each building under analysis. Thereafter, criteria for two key parameters can be applied using HFECs for facility siting purposes with the aim to ensure risk tolerability:

- **Maximum Frequency of Occurrence Threshold** that is considered acceptable and which should be supported by well-known worldwide tolerable risk criteria, internal corporate guidelines, and/or recognized good engineering practices and standards.
- **Minimum Heat Flow Threshold** required to reduce the integrity of the target building and the occupant vulnerability. BEVI **[19]** considers that people located inside the building are protected from heat radiation until the building catches fire. The threshold for the ignition of buildings is set at **35 $kW \cdot m^{-2}$**. If the building is set on fire, a probability of fatality of 1.00 is assumed if the heat radiation exceeds 35 $kW \cdot m^{-2}$ and if lower, no fatalities are considered.

SuperChems™ **[18]** allows the user to quantitatively identify which are the LOCs with higher contribution to the target building and a sensitivity analysis is proposed with the aim to identify which would be the most appropriate and cost-effective risk reduction measures for ensuring risk tolerability compliance (i.e., prevention and/or mitigation measures). A case study has been developed and the performed calculations confirm the following conclusions:

- A risk-based quantitative assessment is the foundation for developing Exceedance Curves. The same risk assessment is also valuable for evaluating occupied buildings due to other impacts; i.e., explosions, flammable/toxic dispersions and for other key purposes such as for complying with individual and societal risk, land-use planning, emergency planning, location of fire and gas detectors (FGS mapping studies).
- Exceedance curves are a good engineering tool suitable to specifically identify whether occupied buildings comply or do not comply with given tolerability facility siting criteria.
- Sensitivity analysis of most contributing outcomes impacting affected buildings is an effective and non-expensive approach for defining appropriate and cost-effective risk reductions measures to be implemented during the decision-making process.

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