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Burning Behavior of Polyurethane Foam Acoustic Insulation used in the Kiss Nightclub Fire

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Abstract

This study evaluates the compartment fire performance of untreated flexible polyurethane foam representative of material installed in the Kiss nightclub, using the NFPA 286 Room Corner Test. Heat release rate was measured by oxygen consumption calorimetry. The material exhibited a peak heat release rate of 2465 kW at 167 s and a total heat release of 142 MJ. The peak value exceeds the 800 kW performance criterion referenced in Annex C.2 of NFPA 286. Total smoke released was 259 m², below the 1000 m² threshold. Sustained burning generated upper-layer temperatures approaching 800°C and incident heat flux exceeding 20 kW/m². Ignition occurred under incident flux between 1–5 kW/m² from pyrotechnic sources. The results indicate high early fire intensity under compartment conditions and demonstrate the importance of heat release rate as a governing parameter in performance-based assessment of interior linings in assembly occupancies.

Keywords: fire safety, insulation foam, nightclub, tests, fire reaction.

1. Introduction

1.1. Fire Risk Scenarios Involving Flexible Polyurethane Foams

In January 2013, a catastrophic fire occurred at Kiss Nightclub in Santa Maria, Rio Grande do Sul, Brazil, resulting in the deaths of 242 individuals and direct injuries to an additional 636 [1]. These figures exclude the broader psychological and emotional impacts endured by the victims' families, friends, and the surrounding community.

The fire was precipitated by the ignition of flexible polyurethane (PU) foam in the sequence of the deployment of a pyrotechnic device during a musical performance by a local pop band in the nightclub. Beyond its alarming mortality rate, this incident is noteworthy for its similarity to other nightclub fires globally. One such loss was the Station Nightclub fire of February 2003, in which an inadequate flexible polyurethane foam, used as an interior finishing, induced the fire to spread violently.

Recurring contributing factors in these incidents include the use of pyrotechnics near acoustic foam, overcrowding, insufficient or nonexistent operational permits, and non-compliance with emergency regulations. These commonalities have been consistently identified across various studies on similar international incidents [2]-[8].

This fire pattern is once again under investigation with another extremely similar fire incident on March 16th, 2025, at the Pulse nightclub in Kočani, North Macedonia, which

killed 59 people and injured 196. This underscores the ongoing need for vigilance in fire prevention, particularly regarding interior finishing materials in nightclubs. Once again, in the case of the fire in North Macedonia, foam played a critical role in the rapid ignition of the fire, in the propagation of flames within the foam itself, and in the production of toxic gases that affected the nightclub occupants."

So, there is a discernible and troubling global pattern in fire disasters occurring in nightclubs and similar high-occupancy entertainment venues, particularly those featuring live music. These fires necessitate rigorous technical and scientific investigation to understand the risks posed not only by ignition sources but, critically, by the interior lining materials, particularly flammable foams and surface finishing, which have consistently played a devastating role in fire development and occupant exposure to lethal smoke.

Studies by Duval [2] and Strick [7] highlight recurring elements in these incidents: ignition dynamics, fire spread mechanisms, and fatality factors. A central aspect in nearly all these fires is the presence of polyurethane foam and other combustible finishing materials, which not only accelerate flame propagation but also produce large volumes of toxic gases such as carbon monoxide, hydrogen cyanide, and isocyanates, contributing significantly to casualties.

The earliest case in this series took place in 2001 at Canecão Mineiro nightclub in Brazil, where 7 people died and 197 were injured [6]. Flammable materials used in the interior finishing, including ceiling linings and decorative elements, played a key role in the rapid fire development. The fire, triggered during a pyrotechnic performance, spread quickly due to the combustible nature of these materials, compromising tenability and making evacuation difficult, despite the building being single-story.

In 2003, the Station nightclub fire in US resulted in 100 deaths and more than 200 injuries, most of them from smoke inhalation during the evacuation phase [4][5]. The fire began when pyrotechnics ignited polyurethane foam panels and curtain fabrics that were used as soundproofing and decorative finishing near the stage. The foam, which lacked any meaningful fire-retardant treatment, ignited within seconds, producing intense flames and a toxic smoke layer that rapidly reduced visibility and tenability throughout the building. The role of polyurethane foam was unequivocally identified as a principal factor both in the rapid fire spread and in the generation of asphyxiating and toxic gases [4][5]. Furthermore, the structure had no sprinkler system and suffered from severely inadequate egress design. In response, NIST [4][5] conducted a comprehensive investigation identifying 26 contributing factors and recommending critical changes to building and fire codes across US, many of these efforts have been directed toward enhancing the treatment, selection, testing, and certification processes for lining and finishing materials, notably including acoustic foams.

A similar tragedy occurred in 2004 in Argentina, at República Cromañón nightclub, where once again the fire was ignited by pyrotechnics and spread rapidly due to the presence of combustible foam materials used on walls and ceilings. This venue, overcrowded with as many as 3,000 occupants, almost triple its official capacity of 1,031, had no valid operating license and lacked compliant emergency exits. The foam linings, originally installed for acoustic purposes, were identified as key contributors to the smoke and heat release rate, which overwhelmed the crowd in a matter of minutes. The emission of dense toxic gases from the foam combustion was a leading cause of fatalities and incapacitation [6].

In 2009, a catastrophic fire broke out at the Lame Horse nightclub in Perm, Russia, resulting in 156 deaths and 78 injuries [7]. Pyrotechnics were again used improperly in a venue lined with combustible materials, including plastic wall claddings and wooden ceiling structures with no fire performance ratings. These materials ignited quickly, fueling the fire and producing dense smoke laced with toxic compounds, which

significantly hampered evacuation. Eyewitness accounts and subsequent investigations described severe problems with emergency egress, further compounding the deadly effects of the rapidly growing fire.

One of the most devastating and widely studied incidents in recent history occurred in 2013 in Brazil, at Kiss nightclub. In this case, acoustic foam made of polyurethane, placed on the ceiling and walls for sound insulation, was ignited by pyrotechnics used during a band performance. The foam burned intensely, releasing a lethal combination of cyanide, carbon monoxide, and other toxic fumes, which spread rapidly through the venue. Studies [2][3][6][7] consistently emphasize that the combustion of polyurethane foam was a was a contributing cause of the high number of fatalities and severe injuries, primarily through its role in rapid fire growth and early development of untenable conditions. While structural and egress issues, such as obstructive guardrails and insufficient exits, played a contributing role, the toxic smoke from the burning foam was a relevant factor that rendered escape impossible for many of the 878 victims affected by the fire.

These incidents collectively underscore the extreme hazard posed by combustible foams and other flammable lining materials in enclosed spaces with high occupant loads. Despite differences in location and context, the recurring presence of polyurethane-based acoustic or decorative materials in these fatal events points to a systemic weakness in fire safety design and regulatory oversight. Some emphasis must be placed on evaluating the fire reaction performance of interior finishing materials, especially in assembly occupancies, where evacuation times are constrained and early smoke development is often the primary threat to life.

In contemporary fire safety science, it is well established that the severity of a fire scenario is governed not by a single material property, but by the interaction between ignition conditions, material response, fire growth dynamics, and the characteristics of the occupancy in which the material is applied [9]. In this context, the heat release rate has long been recognized as the primary variable controlling fire hazard and the development of untenable conditions, as demonstrated in foundational fire science studies [10]. For polymeric materials, particularly flexible polyurethane foams, additional phenomena such as flaming melt dripping, rapid surface involvement, smoke production, and the generation of toxic combustion products further influence fire development and occupant tenability, with their relative importance strongly dependent on the specific fire scenario, including occupant density and available evacuation time.

Previous research [9][10] in the fire materials literature has also highlighted the limitations of commonly used reaction-to-fire tests based primarily on surface flame spread, which may inadequately capture these mechanisms under realistic ignition and exposure conditions. As a result, discrepancies between standardized testing methodologies and real fire scenarios can lead to an overestimation of material fire performance and a false sense of regulatory compliance. Within this framework, the present study adopts a scenario-driven, material-oriented approach to examine the fire behavior of acoustic polyurethane foams, seeking to integrate ignition conditions, heat release characteristics, dripping behavior, smoke and toxicity considerations, and the limitations of existing test methods, with the objective of contributing to evidence-based improvements in the evaluation and regulation of interior lining materials.

Although fire incidents always involve multiple factors and causes[11], the presence of inadequate flexible foams or those with insufficient fire performance is a predominant factor in the outbreak of fires in all these incidents in nightclubs. Acoustic solutions are engineered to optimize sound propagation within the venue while minimizing external sound propagation, thereby mitigating the impact on surrounding areas. Both formal and technical solutions are available, although informal acoustic protection “solutions” are

occasionally employed. Consequently, certain products and materials installed in nightclubs may not exhibit satisfactory acoustic and fire performance.

A common example is polyurethane foam; while some foams provide effective acoustic protection and possess fire-resistant properties, other fail to serve as acoustic barriers and exhibit intense burning when exposed to high temperatures. Lentini [12] has pointed out since 2009 that many furnishings and other fuel packages in a structure may not meet the flammability requirements for interior finishes. These are required to meet certain flame spread specifications or critical heat flux specifications. The use of inappropriate materials has resulted in many tragic fire losses and may be of interest to a fire investigation. In nightclubs, interior finishing are installed for both aesthetic and acoustic purposes.

NFPA 921 [13] states that the composition, thickness, condition, and layers of materials comprising walls, floors, windows, doors, and ceilings should be documented. Therefore, one of the concerns of this study was to properly record the interior finishing of the Kiss nightclub, especially around the main stage. In this context, a physical-chemical analysis focused exclusively on the foam materials was conducted, initially through documentation of similar foams and later by laboratory analyses of the actual foam used at Kiss nightclub.

According to the literature [4][5][11], polyurethane foams exhibit ignition temperatures ranging between 271°C and 378°C. Lentini [12] notes that polyurethane foam has low thermal conductivity (0.034 W/m·K), very low density (20 kg/m³), specific heat capacity (c) of 1,400 J/kg·K, and extremely low thermal inertia (kρc), on the order of 0.000952 × 10^6 $W^2 \cdot s/k^2 \cdot m^4$. Whether or when a target fuel ignites depends on its thermal inertia, and polyurethane foam is one of the materials with the lowest thermal inertia values. The same references state that polyurethane foams can exhibit a heat of combustion of 19.0 kJ/g and a mass loss rate of 35 $kg/m^2 \cdot s$. These values are important for evaluating smoke transport simulations.

Polyurethane foam is highly flammable due to its low density and rapid formation of combustible vapors. It undergoes intense and rapid combustion, significantly contributing to fire propagation and increased compartment temperatures. It is evident that polyurethane (PU) foam poses a substantial risk in fires due to its flammability, high heat release rate, and the gases released during combustion. Lentini [12] remembers that, despite the existing knowledge, further studies are necessary to investigate the specific behaviors of polyurethane foam under various ventilation and confinement conditions.

Numerous studies[2]-[8] indicate that certain foams exhibit high combustibility, a rapid heat release rate, and the production of toxic gases such as hydrogen cyanide (HCN) and carbon monoxide (CO). NFPA sensor921 [13] indicates that hydrogen cyanide (HCN) gas, in addition to carbon monoxide, is another key toxicant that is produced during the combustion of wool, nylon, and plastics, such as polyurethane and ABS, which are commonly found in household furniture and interior finishes.

HCN can act alone or in combination with carbon monoxide (CO) to cause incapacitation and death. HCN can contribute to smoke inhalation deaths by quickly incapacitating fire victims, thereby preventing them from escaping [10]. Dehaan [11] and NFPA 921 [13] demonstrate reasonable disagreement regarding the combined effects of HCN with CO, while the first argues that HCN is always found in combination with CO, but its effects seem to be simply additive, the last one indicates that the effects of CO and HCN are at least additive and may be synergistic. SFPE [14], in turn, points out that in one case where significant concentrations of both CO and HCN were present, the effects were consistent with the toxicity of the two gases being approximately additive. In the end, it is a fact that both gases, combined or not, cause injuries and deaths in fires.

Thus, it becomes evident that, with the recurrence of similar fire incidents, the use of inadequate foam and/or those lacking fire performance results in potential intoxication, deaths and remains a challenge. Irregular foams, without acoustic properties, are part of the problem. However, even professional acoustic foams, marketed by specialized companies and approved in laboratory tests, may sometimes exhibit inadequate fire performance. In such cases, potential failures could stem from the material's manufacturing process, its certification, or regulatory oversight.

In this context, engineers and architects may have studied and complied with the prescriptions of existing codes, and the material may have been inspected and approved by competent authorities. However, a fire could still originate in professional acoustic foam if it lost performance or had its properties altered due to a faulty production process. It is also possible to consider that, in such cases, inadequacy and/or insufficiency does not reside solely in the material itself but also in the prescriptions of fire safety laws and codes.

The recurrence of catastrophic nightclub fires underscores the need for continuity of technical studies aimed at preventing similar tragedies. Investigating the fundamental causes, fire dynamics, and material performance in these incidents is crucial to improving fire safety standards and regulations. Consequently, further research into the thermal behavior of these materials is essential to revise and improve safer fire prevention practices.

Moreover, fire safety studies on foams contribute to the continuous improvement of building codes and fire protection measures. While existing regulations prescribe material performance requirements, the effectiveness of these standards depends on rigorous testing, certification processes, and compliance enforcement. Investigating past fire incidents helps identify regulatory gaps in regulations or in the certification processes, leading to enhanced safety provisions that mitigate potential risks associated with foams.

1.2. The Kiss Nightclub Fire as a Reference Case: Scope, Opportunities, and Objectives of the Present Study

Thus, this study aims to investigate the foam used in the Kiss nightclub and its contribution to the fire, considering both the fire’s outbreak and its role in exacerbating injuries and fatalities. The Kiss Nightclub Fire was specifically chosen for this study because the authors were granted access, prior to the building’s demolition, to visit the site, examine judicial documents, and collect foam samples from the fire scene.

As a result, the specific objectives of this study are: to characterize the thermal decomposition of the foam used in the Kiss nightclub, compare the properties of the generic foam found at Kiss nightclub with those of professional acoustic foams, assess the compliance of the foam used in the Kiss nightclub with fire safety standards and technical regulations, identify gaps in current legislation and inspection processes, and, finally to propose improvements, revisions, and fire safety solutions regarding the use of acoustic foams.

In this study, the term polyurethane foam refers exclusively to flexible polyurethane (PU) foam used as acoustic insulation and interior lining materials. Flexible PU foams are low-density, open-cell polymeric materials commonly employed in sound absorption applications, furniture, and comfort products, and are characterized by low thermal inertia, high porosity, and pronounced melting and dripping behavior under fire exposure. Their fire behavior is therefore fundamentally different from that of rigid polyurethane foams, which are typically closed-cell, higher-density materials used for thermal insulation in building envelopes and sandwich panels, and are regulated under distinct fire performance requirements. Rigid polyurethane foams are outside the scope of the present work. This distinction is well established in the fire science literature[9][15] and

is consistently recognized in classical references on polymer combustion and fire hazard analysis.

Only a limited number of researchers had sufficient time and/or access to the scene of the fire, from a Fire Safety research perspective. Most of the other researchers did not have the opportunity to visit the site, take measurements, examine evidence in situ, collect samples, or access documents, in short, to substantiate their work with real data and information. In a significant portion of the existing reports, there is no evidence of the use of a specific, organized, and consolidated fire investigation methodology.

Thus, given the scenario above, some favorable prospects emerge from the investigation proposed herein. The present study had adequate time for its development. Multiple sources of information were sought in order to investigate as many details as possible about the fire's origin. It was possible to inspect the site, which remained sufficiently preserved in 2022, still retaining characteristics and even original objects from the fire, as shown in Figure 1 to Figure 4.



Figure 1 - Kiss night club in 2022



Figure 2 - The main stage (area of origin of fire)



Figure 3 - The wall of the main dance floor



Figure 4 - The exit of the main dance floor

Consequently, it was possible to analyze existing blueprints of the site, verify and revise the exact dimensions of the building, request local documents, and conduct interviews with victims, firefighters who responded to the incident, and individuals related to the fire. Additionally, evidence was examined and original samples of the foam used in the Kiss nightclub were collected. With further evidence available, specific full-scale fire tests were carried out to study scenarios closely resembling those of the actual day of the fire.

Furthermore, this study included numerical measurements of time, temperature, and heat flux. The likely artifacts associated with the fire's origin were also analyzed.

The European Network of Forensic Science Institutes (ENFSI) [17] prescribes, as best practices in fire investigation, the execution of physical tests such as full-scale reconstructions and computational modeling. Furthermore, it recommends that the investigative methodology be adaptable to the specific characteristics of each fire incident. So, given the availability of actual foam samples from the Kiss nightclub, laboratory analyses, full-scale tests, and computational simulations were prioritized.

In addition to laboratory analyses, this study includes full-scale fire testing and quantitative measurements, using foam similar to that found in the Kiss nightclub (since the foam samples collected from the nightclub were limited in quantity and size). Based on the results of these analyses and tests, it was possible to support scenarios that closely resemble the actual conditions at the Kiss nightclub. The results of these procedures have the potential to support hypothesis testing as outlined in the Scientific Methodology described in NFPA 921 [13].

Finally, this study employed methodologies specifically designed and validated for fire investigations that aim to provide feedback for and enhance Fire Safety practices. The present work was extensively based on the methodologies proposed by Freitas and Rodrigues [19], and secondarily on NFPA 921 [13]. This study is specifically limited to investigating the origin of the fire and the first material ignited at the Kiss nightclub, with a focus on identifying the first ignited fuel.

It is not within the scope of this study to detail the analyses of fire propagation and resulting damage in the building. Furthermore, the experimental tests developed here were conducted under ventilated conditions (as in the real Kiss nightclub fire); thus, this work does not present combustion results in under-ventilated conditions or characteristics of confined environments (since these were not the initial conditions of the Kiss nightclub fire).

2. Fire Risk Scenario and Experimental Investigation

2.1. Definition of the Fire Risk Scenario

The fire risk scenario examined in this study is associated with a high-occupancy assembly environment, specifically a nightclub operating as an enclosed entertainment venue with live musical performances. Such occupancies are inherently vulnerable to rapid fire development due to elevated occupant density, limited tolerance to smoke production, and reduced available safe egress time during the early stages of a fire.

The spatial configuration of the Kiss nightclub played a central role in the development of the fire. The main stage was located at one end of the primary dance floor and was surrounded by interior lining materials installed primarily for acoustic purposes. Flexible polyurethane (PU) foam panels were applied to both the walls and the ceiling of the stage area, as illustrated in Figure 5 and Figure 6.

According to the Civil Police investigation report [1], the bartender himself stated during formal testimony that he purchased the polyurethane foam panels from a mattress store and personally installed them on the main stage using shoe adhesive, acting under instructions from one of the nightclub’s owners. This application of foam panels on the stage walls and ceiling was carried out without technical supervision by engineers or architects [1]. The panels were installed near ignition sources associated with stage performances and to electrical installations, resulting in exposure of the combustible foam surfaces to open flames, heated surfaces, and potential localized heat sources.



Figure 5 - Stage on day of the incident [22]

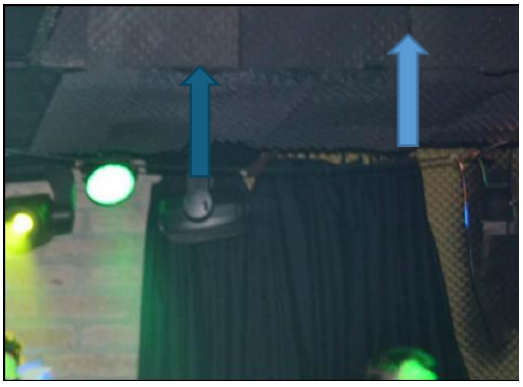


Figure 6 - Arrangement of PU panels [22]

The foam panels were installed without a continuous protective barrier and were manually cut from larger foam sheets, resulting in a non-uniform arrangement with gaps between adjacent panels (see Figure 6). These gaps created recessed and irregular surfaces capable of trapping incandescent particles and hot residues generated by the pyrotechnic device, increasing the contact time between the ignition source and the combustible material. In contrast to a professionally installed, the discontinuous foam configuration facilitated the lodging and persistence of heated particles. This installation condition therefore significantly increased the likelihood of ignition by prolonging localized thermal exposure.

The ignition source relevant to this scenario was a pyrotechnic device used during a musical performance. Available video evidence [21] and documentation [1] indicate that the device produced an open flame accompanied by incandescent particles, which directly impinged on the foam lining installed on the ceiling and walls of the main stage. Frames extracted from a cellphone video recorded by a nightclub occupant [21] capture the initial ignition and the immediate attempt to extinguish the flames using a portable fire extinguisher (Figure 7). The pyrotechnic device employed was intended for outdoor use, and its packaging explicitly indicated restrictions against use in enclosed or covered spaces. No technical datasheet or safety information sheet was available for the device.



a) b) c)

Figure 7 - Video frames of the initial fire ignition near the main stage: (a) 0 s, (b) 12 s, (c) 16 s. [21]

The interior finishing materials of the nightclub were varied and included fabrics such as curtains, plastic components such as televisions, loudspeakers, and seating elements, as well as wooden flooring. The ground-floor ceiling was constructed of plasterboard,

while the mezzanine ceiling exposed portions of the roof structure. Both the stage floor and the main dance floor were made of wood, with a raised wooden floor present in the main dance area. Computational reconstructions developed after the fire, particularly those produced by the Federal University of Santa Maria [26] and validated using post-fire photographic evidence, illustrate the distribution of interior finishing materials and support the spatial characterization presented in this study (Figure 8 and Figure 9).



Figure 8 – Reconstitution of dance floor [26]



Figure 9 – Dance floor after fire [26]

Above the main stage, a large air-conditioning duct was installed. Flexible polyurethane foam panels were applied not only to the rear and side walls of the stage, but also near the duct. As illustrated in Figure 10, this configuration placed combustible foam directly adjacent to stage-related ignition sources and around a fixed obstruction, increasing exposure to heat and flames while simultaneously limiting direct access for early manual fire suppression, particularly in the narrow space between the upper surface of the duct and the ceiling. In addition, the air-conditioning duct included an outlet projecting conditioned air into the stage area, a feature that is relevant to the initial ventilation conditions of the fire scenario.

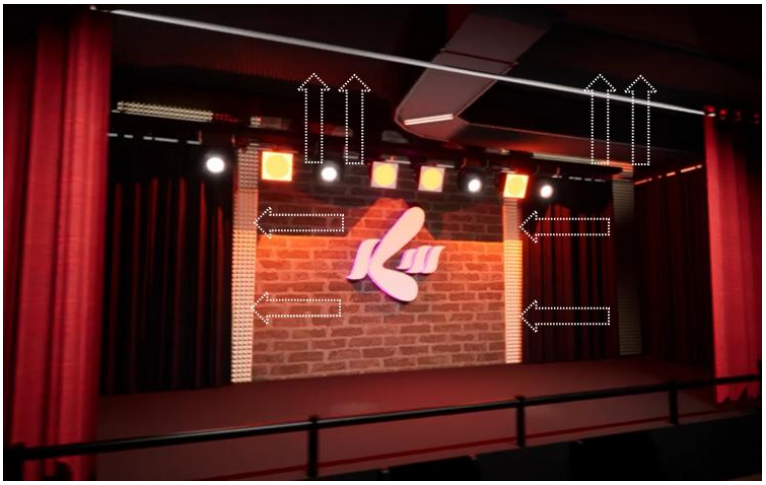


Figure 10 – Main stage reconstituted [26]

Ventilation conditions played a critical role in the early development and subsequent aggravation of the fire. During the initial phase, mechanical ventilation associated with the air-conditioning system likely contributed to the supply of oxygen and to the transport of combustion products within the enclosure, as reported by witnesses [1] who stated that both lighting and air-conditioning systems remained operational immediately after ignition. As the event progressed, however, electrical power to the building was lost, resulting in the shutdown of the lighting system. It is therefore reasonable to infer,

although this cannot be confirmed with certainty, that the air-conditioning system also ceased operation at that stage.

From that point onward, the nightclub effectively behaved as a sealed enclosure with severely limited ventilation. No windows or secondary doors were present (although an exhaust duct was present near the restroom area, its external termination was sealed with ceramic masonry, rendering it non-functional and preventing any effective exhaust to the exterior). The only available opening for both air entrainment and the discharge of hot gases and smoke was the main entrance, which simultaneously served as the primary means of egress for occupants. Consequently, the fire transitioned from an initially mechanically ventilated condition to a predominantly under-ventilated regime, in which the same opening was required to sustain combustion while also functioning as the sole escape route. This configuration substantially exacerbated fire growth, smoke accumulation, and tenability conditions within the space.

Several aggravating conditions were present and are relevant for characterizing the severity of the scenario, although they are not the primary focus of this study. These include a high occupant load, insufficient and inadequate means of egress, and the absence of active fire protection systems. While these factors influenced the consequences of the event, the present work focuses on the interaction between the ignition source, the combustible foam lining, and the environmental conditions governing the initial stages of fire development.

Taken together, the fire risk scenario here addressed is defined by the interaction of a real pyrotechnic ignition source with exposed flexible polyurethane acoustic foam installed on horizontal, vertical and overhead surfaces within a confined, high-occupancy assembly space. Ventilation conditions that initially supported combustion and later transitioned toward limited air supply further contributed to rapid fire development. This scenario constitutes the reference framework for the experimental approach adopted in this work and provides the basis for interpreting the results of tests presented in the following sections.

According to the framework discussed by Gorbett et al. [27] patterns of thermal damage and material degradation provide valuable information regarding fire severity, spatial gradients of heat exposure, and the interaction between combustible materials and the fire environment. In the Kiss nightclub, post-fire damage patterns indicate that the stage area experienced particularly severe fire effects, including extensive consumption of interior linings and significant degradation of structural and finishing elements. Consistent with the concepts discussed by Gorbett et al. [27], these indicators reflect a localized region of high heat release and rapid fire development.

From the perspective of fire risk assessment and material behavior, this makes the stage area a critical zone for analysis, as it concentrates multiple factors relevant to fire growth, including ignition proximity, combustible polyurethane foam linings, and enclosure effects. Accordingly, the observed damage patterns support the selection of this area and its materials as the focus of the experimental investigations presented in the following sections, aimed at better understanding the role of polyurethane foam in rapid fire development under realistic conditions.

2.2. Non-standardized Full-Scale Reconstruction (Container Test)

This study incorporates two distinct full-scale experimental approaches with different methodological status. First, a non-standardized full-scale container reconstruction test was conducted and is presented in this section (Section 2.2) to reproduce the ignition scenario under controlled but non-normative conditions. Second, a standardized full-scale NFPA 286 room-corner test was performed by an accredited laboratory to obtain

quantitative fire performance data under a defined compartment protocol; this second experimental program is described in detail in a subsequent section. The two approaches serve complementary purposes and should not be interpreted as methodologically equivalent.

2.2.1. Experimental Setup and Procedures of the Full-Scale Reconstruction Test

The full-scale fire tests were conducted to reproduce, as closely as practicable, the ignition conditions and early fire development observed in the Kiss nightclub fire, with specific emphasis on the interaction between pyrotechnic ignition sources and flexible

polyurethane foam applied to ceiling surfaces. The experimental approach intentionally prioritized realism of ignition mode, spatial configuration, and material interaction over strict adherence to small-scale standardized testing protocols.

The experiments were performed inside a closed metallic test compartment constructed of steel panels. The internal dimensions of the compartment were sufficient to allow the installation of ceiling-mounted materials and the positioning of a full-size anthropomorphic mannequin. No forced ventilation was provided during the test sequence; only ambient air exchange was present prior to ignition. All internal surfaces of the enclosure were non-combustible.

Although the tests were conducted inside a metallic compartment, the ignition area was intentionally positioned near the entrance opening rather than deep inside a fully enclosed configuration. This decision was motivated by two factors. First, safety considerations required avoiding the accumulation of combustion gases and smoke from polyurethane foams without certified fire performance, particularly the mattress-store foam, which could generate significant toxic effluents and create hazardous conditions for personnel and subsequent experimental activities. Second, the early phase of the Kiss nightclub fire occurred under ventilated conditions, as the ignition source was located near an operating air-conditioning outlet, which reportedly remained active during the initial moments of the event [1]. Therefore, positioning the ignition zone closer to the compartment opening allowed partial ventilation consistent with the early fire development scenario, while maintaining controlled experimental conditions. This approach reflects the initial ventilated stage of the nightclub fire rather than the later under-ventilated phase that developed after electrical failure and smoke accumulation.

A removable ceiling panel was installed at the upper portion of the compartment to simulate a horizontal overhead surface. Rectangular plates of flexible polyurethane foam were mounted directly onto this ceiling panel, one per manufacturer at a time, with the foam surfaces oriented horizontally and facing downward toward the ignition source. The mounting configuration intentionally reproduced an exposed installation, without any continuous protective barrier or thermal shielding layer between the foam and the ignition source.

Three distinct types of flexible polyurethane foam were tested in separate experimental runs. The (i) first type consisted of foam obtained from a mattress retail store, without any declared or certified fire-retardant treatment (hereafter designated as “mattress-store polyurethane foam no declared fire-retardant treatment”). This material was selected because it followed the same acquisition pathway described in the official investigation of the Kiss nightclub fire, in which foam was reportedly purchased from a mattress store and installed without technical supervision. The objective was to reproduce, as closely as practicable, a material representative of that procurement process, rather than to rely on specialized acoustic products with certified fire performance.

It is important to clarify that the recovered Kiss nightclub foam was preserved primarily for the standardized NFPA 286 room-corner testing phase, which required controlled

installation and sufficient surface area for compartment evaluation. Although the recovered material consisted of multiple segments (Figure 11) rather than a single continuous sheet, the available quantity allowed assembly into the configuration required for the NFPA 286 test.

In order to preserve the maximum amount of original material for this standardized evaluation, the non-standardized full-scale reconstruction conducted in the container environment employed commercially acquired mattress-store polyurethane foam obtained through the same procurement pathway described in the official investigation. This allocation strategy ensured that the compartment-scale performance metrics reported under NFPA 286 correspond directly to the original Kiss nightclub material, while the reconstruction phase maintained scenario fidelity without consuming the preserved evidence.



Figure 11 – "Real" acoustic foam of the Kiss night club collected in 2022

The (ii) second and (iii) third foam types were commercially manufactured products obtained from two different suppliers (hereafter designated as "declared fire-retardant polyurethane foam – Supplier A" and "declared fire-retardant polyurethane foam – Supplier B"), each accompanied by technical documentation and formal declarations of fire-retardant properties. These materials were selected for comparative purposes, allowing evaluation of how products marketed with declared fire performance characteristics would behave under the same full-scale ignition conditions. Although both products were presented by their respective manufacturers as possessing fire-retardant properties, their behavior under realistic pyrotechnic exposure differed. One of the declared fire-retardant foams (Supplier B) exhibited ignition and fire development characteristics comparable to the untreated mattress-store foam, whereas the other demonstrated (Supplier A) substantially improved resistance to ignition and reduced fire growth under the same conditions. Detailed comparative results are presented in the subsequent section.

In addition to the ceiling-mounted foam, a vertically installed (iv) textile curtain was positioned in close proximity to the foam plate. The foam was mounted horizontally overhead, while the curtain was installed vertically on the rear wall of the compartment. This configuration was intentionally designed to allow observation of two potential ignition pathways: direct ignition of the foam by the pyrotechnic device, and secondary ignition of the curtain due to flame spread or molten dripping from the burning foam. The relative positioning enabled assessment of whether flaming droplets or hot residues from the foam could act as secondary ignition sources for adjacent combustible materials, a mechanism considered relevant to enclosure fire development in stage environments.

A full-size anthropomorphic mannequin was positioned directly below the ceiling-

mounted foam plate. The mannequin was fixed in a standing posture, with the torso upright and the head-oriented forward. One articulated arm was raised above shoulder level, reproducing the posture observed in video records of the Kiss nightclub fire, in which a performer activated a pyrotechnic device with the arm elevated toward the stage ceiling. The mannequin remained stationary throughout each test.

The pyrotechnic device was positioned in the raised hand of the mannequin and secured using thin metallic wire to maintain a consistent vertical orientation throughout each test. Although the mannequin arm was kept at the same elevation in all experiments, minor variations in the overall length of the individual pyrotechnic devices resulted in small differences in the absolute distance between the device outlet and the ceiling-mounted foam. These variations were documented but did not alter the overall geometric configuration, as the device outlet remained approximately 0.50/0.40 m below the foam surface in all test runs.

Three distinct pyrotechnic devices were tested in separate experimental runs. The (a) first device was a low-intensity outdoor-use consumer firework commercially known as “Chuva de Prata” (Silver Rain). This device produces a relatively limited projection of sparks and is commonly marketed for recreational use, including use by children. Notably, this type of device was identified in official documentation related to the Kiss nightclub event as part of the pyrotechnic materials used during musical performances. The device is classified as a “hot spark” firework and is not rated for indoor use.

The (b) second device tested was an outdoor-use pyrotechnic device known as “Sputnik.” In contrast to the Silver Rain, this device produces a more intense and higher-energy projection of sparks, with greater heat release and spark throw distance. Like the first device, it is classified as a “hot spark” firework intended for outdoor environments and is not certified for enclosed indoor use.

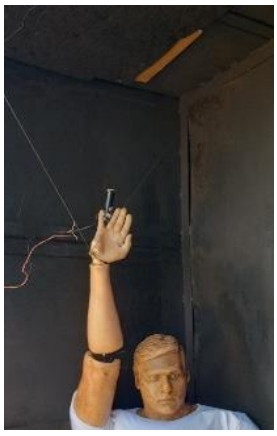


Figure 12 – Assembling of the real scale test



Figure 13 – Noncertified foam, being exposed to the heat source (scenario 3)



Figure 14 - Noncertified foam, after being exposed to the heat source (scenario 3)

The (c) third device tested was a professional pyrotechnic effect classified for indoor applications, commonly referred to as a “Gerb.” This device is marketed as a “cold spark” effect and is designed to produce controlled spark emissions with reduced flame propagation potential compared to outdoor-use fireworks. It is typically used in stage productions under regulated conditions and with appropriate safety clearances.

In each experimental run, only one pyrotechnic device was activated. The ignition angle was maintained in a vertical upward orientation, and the spark projection was aligned toward the central region of the ceiling-mounted foam plate. This configuration ensured direct impingement of sparks and hot residues onto the foam surface under controlled

and repeatable geometric conditions.

Prior to ignition, the vertical distance between the outlet of the pyrotechnic device and the lower surface of the foam plate was measured using a tape measure and documented photographically. This distance was approximately 0.50 m and was kept consistent across all test configurations to ensure repeatability and allow direct comparison between different foam plates and pyrotechnic devices. The selected distance was representative of the geometric conditions present in the Kiss nightclub, where the ceiling height was low and the pyrotechnic device was discharged in close proximity to the ceiling lining, as Figure 12 and Figure 14 show.

Ignition of the pyrotechnic device was performed manually using an open flame applied directly to the device fuse. The ignition source was brought into contact with the fuse tip, and the experimental time reference was initiated immediately upon visible ignition of the fuse. Following ignition, continuous visual observation was conducted to document spark emission, contact between projected particles and the foam surface, ignition onset (if any), flame attachment, flame spread, dripping behavior, and smoke production. No suppression measures were applied during the ignition and early growth phase, allowing free and unobstructed development of the fire behavior under the defined geometric conditions.

Temperature measurements were obtained using five thermocouples installed at predefined locations within the experimental configuration to characterize thermal development during ignition and early fire growth. Two thermocouples were positioned directly on the surface of the ceiling-mounted foam plate, forming two measurement points intended to record the temperature rise resulting from the combined effect of pyrotechnic spark impingement and subsequent foam combustion. These sensors were used to quantify the thermal exposure at the material surface and to allow comparative assessment of temperature evolution across the different foam types tested.

A third thermocouple was positioned immediately above the pyrotechnic device outlet (Figure 15), aligned with the vertical axis of spark projection. This sensor was intended to measure the thermal output generated by the pyrotechnic device under the defined geometric conditions. Owing to the intensity and directional force of the spark emission, this thermocouple was occasionally subjected to direct impingement by hot particles, which could result in minor mechanical displacement during the test. This effect was anticipated and considered representative of realistic exposure conditions associated with spark projection.

Two additional thermocouples were installed on the anthropomorphic mannequin: one at the hand holding the pyrotechnic device and another at the chest region. These sensors were intended to measure the temperature exposure potentially experienced by a human body located in close proximity to both the ignition source and the burning foam. In addition to recording convective and radiative heat transfer, these thermocouples were capable of detecting localized temperature spikes associated with flaming molten droplets falling from the foam. Such measurements were relevant to evaluating the potential thermal impact on skin-analog locations in scenarios involving direct contact with burning polymer drips.

A primary Gardon-type heat flux gauge was installed near the entrance region of the test compartment at approximately 2.50 m above floor level (Figure 16). The sensor was oriented toward the ceiling assembly, directly facing the foam-mounted surface, and was used to quantify the total incident heat flux during ignition and early fire development, capturing both radiative and convective components. In addition, a second Gardon-type heat flux gauge was installed at a lower elevation within the enclosure to predominantly measure radiative heat flux. However, the primary analysis presented in this study is based on the measurements obtained from the 2.50 m instrument.



Figure 15 – Allocation of the thermocouple, above Silver Rain



Figure 16 – Allocation of heat flux sensor (Gardon gauge)

During each test, qualitative observations were systematically recorded, including the time to visible ignition of the foam, flame attachment to the foam surface, flame spread patterns, occurrence and behavior of molten or burning droplets, interaction between dripping material and lower surfaces, smoke production characteristics, and visual impacts on the curtain and mannequin. Wind speed and direction were not instrumentally recorded during the reconstruction test.

Each test was terminated after the ignition and early fire growth phase had been sufficiently observed. The compartment was allowed to cool naturally before any materials were removed. After each test, the foam plate and pyrotechnic device were replaced, the curtain was exchanged if significantly damaged, and the mannequin position was verified to ensure consistency across subsequent test runs.

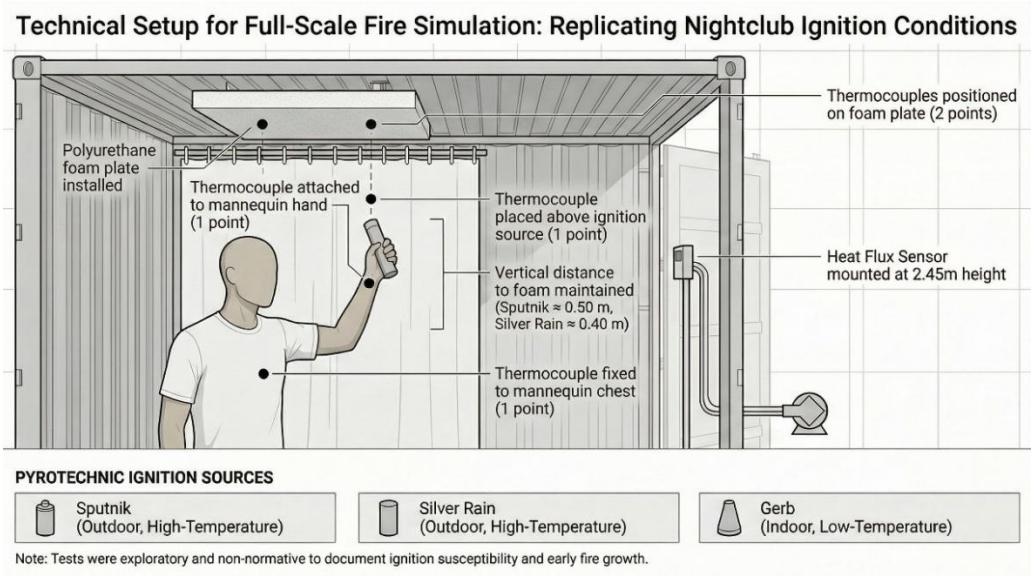


Figure 17 – Experimental Configuration of the Full-Scale Reconstruction Test Setup

Figure 17 schematically summarizes the reconstruction experimental configuration, illustrating the metallic enclosure, ceiling-mounted polyurethane foam plate, vertical fabric curtain, mannequin with elevated arm holding the pyrotechnic device, thermocouple positions, and the primary heat flux gauge positioned at 2.50 m above the floor. A second heat flux gauge was also installed during testing, although it is not

represented in the schematic. Together, these instruments allowed characterization of the thermal exposure field during the full-scale reconstruction tests.

These full-scale tests were not intended to generate standardized fire performance indices. Instead, they were designed to document ignition susceptibility and early fire growth behavior under a realistic fire risk scenario involving pyrotechnic ignition and flexible polyurethane foam.

2.2.2. Results of Full-Scale Reconstruction Tests

a) Ignition Occurrence Across Test Scenarios

A total of twelve experimental scenarios were established, combining four potential first fuels and three pyrotechnic heat sources, as described in the experimental methodology. The objective of this phase was to determine whether sustained flaming ignition of the selected material occurred under direct spark impingement from each pyrotechnic device. The ignition outcomes for all configurations are summarized in Table 1.

Table 1 - Scenarios established in the experimental tests

Scenarios	Considered first fuel	Considered heat source	Fire ignition
1	Mattress-store polyurethane foam[I]	Purple rain (outdoor)	**YES**
2	Mattress-store polyurethane foam[I]	Gerb (indoor)	NO
3	Mattress-store polyurethane foam[I]	Sputnik (outdoor)	**YES**
4	Declared fire-retardant foam - Supplier A[II]	Purple rain (outdoor)	NO
5	Declared fire-retardant foam - Supplier A[II]	Gerb (indoor)	NO
6	Declared fire-retardant foam - Supplier A[II]	Sputnik (outdoor)	NO
7	Declared fire-retardant foam - Supplier B[III]	Purple rain (outdoor)	NO
8	Declared fire-retardant foam - Supplier B[III]	Gerb (indoor)	NO
9	Declared fire-retardant foam - Supplier B[III]	Sputnik (outdoor)	**YES**
10	Curtain Fabric [IV]	Purple rain (outdoor)	NO
11	Curtain Fabric [IV]	Gerb (indoor)	NO
12	Curtain Fabric [IV]	Sputnik (outdoor)	NO

Observations
I – A generic foam, purchased from a mattress store, without technical manual or product catalog.
II – Professional acoustic foam, manufactured by “company A”, purchased from a specialized store, with technical manual and product catalog. The vendor provided laboratory fire performance exam reports.
III – Professional acoustic foam, manufactured by “company B”, provided by a specialized commercial representative for academic research purposes, with technical manual and product catalog. The commercial representative provided laboratory fire performance exam reports.
IV – Curtain fabric similar in texture and composition to the one observed at Kiss nightclub.

The mattress-store polyurethane foam (no declared fire-retardant treatment) exhibited sustained flaming ignition in two of the three exposure conditions. Ignition was observed when this material was exposed to the outdoor-use pyrotechnic devices “Silver Rain” and “Sputnik”. Under exposure to the indoor-rated “Gerb” device, no sustained flaming was observed.

The declared fire-retardant polyurethane foam from Supplier A did not exhibit sustained ignition in any of the three exposure scenarios. Direct spark impingement occurred under all configurations; however, no persistent flaming developed following exposure to the “Silver Rain,” “Sputnik,” or “Gerb” devices. In certain instances, localized surface degradation was observed at the point of spark contact, resulting in limited material consumption and the formation of small, discrete cavities in the foam matrix. These effects were restricted to the immediate impingement zone and did not evolve into sustained flaming, visible smoke production attributable to the foam, or horizontal or vertical flame propagation across the panel surface. No molten dripping was observed, and no secondary ignition of adjacent materials occurred.

In contrast, the declared fire-retardant polyurethane foam from Supplier B exhibited sustained flaming ignition in one of the three tested configurations. Ignition occurred

when exposed to the “Sputnik” device, while no sustained flaming was observed under exposure to “Silver Rain” or “Gerb.” Once ignited, the material exhibited extensive degradation, with near-total consumption of the exposed foam panel, in contrast to the localized and self-limited degradation previously observed for Supplier A.

The vertically installed textile curtain did not exhibit sustained ignition in any of the tested exposure conditions. Direct spark contact resulted in localized surface damage and scorching; however, no persistent flaming developed in the absence of prior foam ignition. In scenarios where ignition occurred within the enclosure, flaming of the polyurethane foam preceded any involvement of the curtain. Based on these observations, the textile curtain was not considered a viable first fuel under the defined ignition conditions and was excluded from subsequent comparative evaluation of ignition susceptibility.

The ignition matrix demonstrates clear differentiation in material response under identical spatial and exposure conditions. The mattress-store polyurethane foam exhibited the highest ignition susceptibility among the materials tested. The declared fire-retardant polyurethane foam from Supplier B demonstrated limited but measurable ignition vulnerability under high-energy spark exposure, whereas the declared fire-retardant polyurethane foam from Supplier A did not ignite in any tested configuration. These findings establish the basis for further examination of sustained flaming behavior, flame spread characteristics, dripping phenomena, and thermal output in the subsequent sections.

b) Flame Attachment and Early Fire Growth

Following sustained flaming ignition, clear differences were observed in flame attachment and early fire growth among the tested materials, consistent with the qualitative assessment presented in Table 2 and the material classification defined in Table 1.

Table 2 - Qualitative and Descriptive Observations of the Full-Scale Reconstruction Tests

	Mattress-store polyurethane	Declared fire-retardant foam - Supplier A	Declared fire-retardant foam - Supplier B
Transition to Sustained Flaming under “Gerb Indoor” Exposure	Not observed	Not observed	Not observed
Transition to Sustained Flaming under “Purple Rain” Exposure	Observed (Purple rain) (Sputnik)	Not observed	Not observed
Transition to Sustained Flaming under “Sputnik” Exposure	Observed (+++) (Figure 13) (Purple rain) (Sputnik)	Not observed	Observed (+) (Sputnik)
Post-Ignition Surface Flame Propagation	Observed (+++) (Figure 13) (Purple rain) (Sputnik)	Not observed	Observed (+) (Sputnik)
Post-Ignition Flaming Melt-Dripping Behavior	Observed (+++) (Figure 13) (Purple rain) (Sputnik)	Not observed	Observed (+) (Sputnik)
Thermal Decomposition and Structural Mass Loss	Complete (+++) (Purple rain) (Sputnik)	Very limited and localized (Sputnik)	Extensive (+) (Sputnik)
Post-Ignition Smoke Production and Visual Obscuration	Smoke from foam (+++) (Purple rain) (Sputnik)	Only smoke from the pyrotechnic device	Smoke from foam (+) (Sputnik)

Comparative scale, by visual observation:
(+++): Higher quantity, frequency, or speed observed.
(+): Lower quantity, frequency, or speed observed.

For the Mattress-store polyurethane foam, sustained flaming ignition occurred under exposure to the “Purple rain” and “Sputnik” pyrotechnic devices. Once ignition was established, the flame did not remain confined to the initial spark impingement zone. Stable flame attachment to the foam surface was observed, with immediate involvement of adjacent cells in the polyurethane matrix. The flame adhered to the surface and propagated horizontally across the exposed face of the panel.

Early fire growth was rapid. The flaming area expanded progressively from the point of ignition to generalized surface involvement, resulting in near-complete consumption of the panel in the tested configuration. This behavior corresponds to the qualitative classification (+++) for flame spread and material degradation shown in Table 2. The sustained surface flame promoted continuous thermal decomposition of the foam, reinforcing flame attachment and accelerating the growth phase.

In contrast, the declared fire-retardant foam from Supplier A did not exhibit sustained flaming ignition in any of the tested scenarios. Although direct spark impingement produced localized surface degradation at the contact points, no stable flame attachment developed at any time. The degradation remained restricted to small, superficial cavities, and no horizontal or vertical flame spread was observed. Consequently, no early fire growth phase was established for this material under the defined ignition conditions.

The declared fire-retardant foam from Supplier B demonstrated intermediate behavior. Sustained flaming ignition was observed only under exposure to the “Sputnik” device. In this configuration, flame attachment to the surface occurred and propagated beyond the initial ignition point. However, the rate and extent of surface involvement were lower than those observed for the mattress-store polyurethane foam, consistent with the qualitative classification (+) for flame spread and degradation in Table 2. Despite this reduced intensity, early fire growth progressed sufficiently to result in extensive degradation of the exposed panel in the ignition scenario.

In all scenarios where sustained flaming developed, flame attachment was visually associated with progressive structural collapse of the polyurethane matrix and increasing flame height during the early growth stage. Smoke production attributable to foam combustion was observed for the Mattress-store polyurethane foam and for the declared fire-retardant foam from Supplier B under the ignition scenario, whereas no sustained smoke generation from the foam was observed for the declared fire-retardant foam from Supplier A.

Under identical geometric and exposure conditions, the transition from ignition to stable surface flame attachment and early fire growth varied significantly among the tested materials. The mattress-store polyurethane foam exhibited rapid and generalized flame attachment with accelerated early fire growth. The declared fire-retardant foam from Supplier B showed limited but measurable susceptibility under high-energy exposure. The declared fire-retardant foam from Supplier A did not progress beyond localized surface degradation and did not enter a sustained flaming regime.

c) Dripping Behavior and Secondary Ignition Potential

Dehaan affirms [11] that as polyurethane foams burn, they decompose and “melt” into a semi-liquid state that pools beneath the chair, sofa, or mattress, sustaining a very intense pool fire. Flaming melt-dripping was observed during the combustion of the mattress store polyurethane foam and, under one configuration, the declared fire retardant foam from Supplier B. No dripping was recorded in any scenario involving the declared fire

retardant foam from Supplier A.

For the mattress store polyurethane foam, once sustained flaming and generalized surface involvement were established, progressive thermal degradation led to softening and partial liquefaction of the polyurethane matrix. Molten material accumulated along the lower edges of the panel and detached in the form of droplets. Several droplets were visibly flaming at the moment of detachment, and combustion persisted during free fall.

Figure 18 and Figure 19 document representative impacts of flaming droplets on the mannequin positioned beneath the foam panel. The molten material penetrated the cotton shirt, producing perforations and localized charring of the fabric. The close-up image shows deep surface degradation of the underlying mannequin substrate directly beneath the textile layer, indicating concentrated heat transfer at the point of contact. The damage pattern demonstrates that the droplets were not limited to passive hot residues; they retained active flaming combustion and sufficient thermal energy to cause localized destructive effects upon impact.

The computational simulation conducted in a separate study, using material properties derived from the tested foam, reproduced the melt-dripping phenomenon and indicated the formation of elevated temperature zones at the floor level beneath the burning panel. The simulation output (Figure 20) shows concentrated hot regions corresponding to areas where flaming droplets accumulated, supporting the experimental observation of secondary thermal intensification below the primary ignition surface.



Figure 18 – Dripping of hot residues on a shirt



Figure 19 – Dripping of hot residues on a body

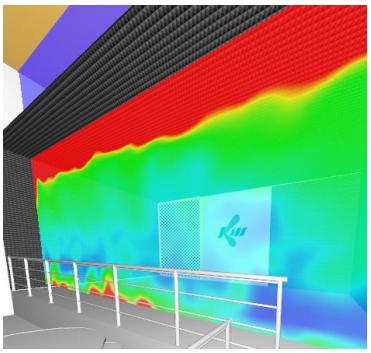


Figure 20 – Dripping of hot residues in the computational simulation

In addition to direct impingement on the mannequin, flaming droplets accumulated on the floor surface. Small localized burning zones were observed where molten residues pooled, forming secondary flaming areas independent of the original panel surface. These localized flames persisted after detachment, evidencing sustained combustion of the dripping material.

The declared fire retardant foam from Supplier B exhibited similar behavior only in the configuration where sustained flaming ignition occurred (exposure to the “Sputnik” device). Under that condition, melt-dripping was observed with lower frequency and smaller droplet size compared to the mattress store polyurethane foam. Flaming droplets detached intermittently and produced localized burning on lower surfaces, consistent with the qualitative classification (+) presented in Table 2.

In contrast, the declared fire retardant foam from Supplier A did not exhibit melt-dripping in any tested configuration. Although localized surface degradation occurred under direct spark impingement, the material did not transition into a semi-liquid state, and no molten residue detachment or secondary flaming below the panel was recorded.

Under identical geometric and exposure conditions, the dripping propensity differed

markedly among the materials. The mattress store polyurethane foam demonstrated frequent flaming melt-dripping with sustained combustion after detachment and clear secondary ignition potential. The declared fire retardant foam from Supplier B showed limited but measurable dripping under sustained flaming conditions. The declared fire retardant foam from Supplier A did not exhibit dripping or secondary ignition phenomena in any experimental scenario.

d) Thermal Exposure: Temperature and Heat Flux Measurements

For clarity of comparative analysis, subsequent discussion of thermal exposure focuses primarily on the two bounding performance conditions observed: the declared fire-retardant foam from Supplier A and the untreated mattress-store polyurethane foam. The intermediate behavior exhibited by Supplier B was documented in the recorded measurements; however, because its response consistently fell between the non-ignition performance of Supplier A and the sustained flaming behavior of the untreated foam, the most technically relevant contrast lies between these two limiting cases.

Quantitative thermal measurements were recorded for all experimental scenarios using thermocouples and heat flux gauges positioned as described in Section 2.2.1. The instrumentation allowed simultaneous monitoring of temperature evolution at multiple vertical levels and measurement of incident heat flux heat flux under both combined convective–radiative conditions and predominantly radiative conditions, as Figure 21 to Figure 28 show.

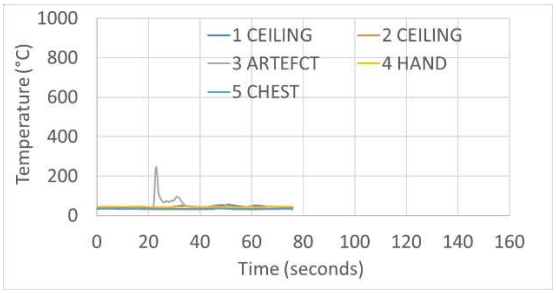


Figure 21 – Temperature, silver rain X foam from Supplier A

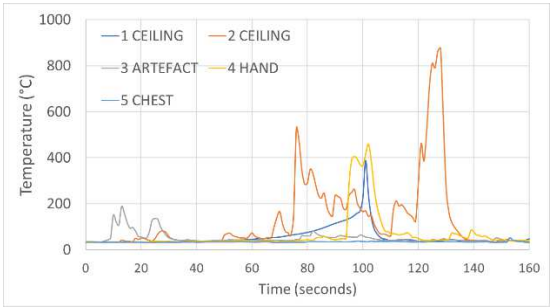


Figure 22 – Temperature, silver rain X mattress store polyurethane foam

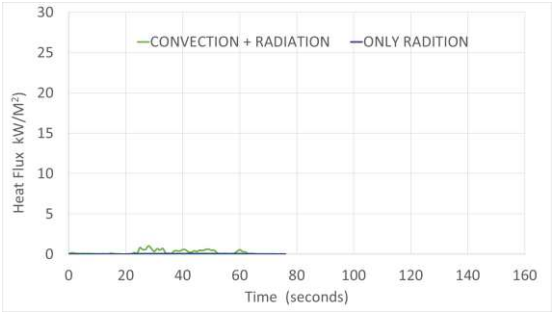


Figure 23 – Heat flux, silver rain X foam from Supplier A

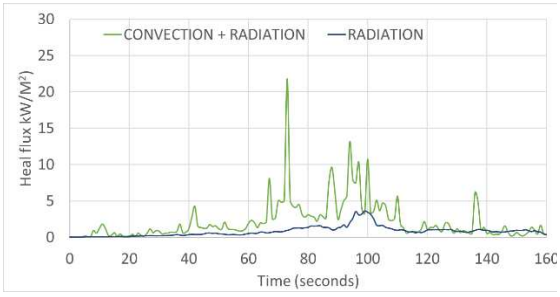


Figure 24 – Heat flux, silver rain X mattress store polyurethane foam

In scenarios where no sustained flaming ignition occurred, temperature and heat flux curves remained close to baseline values and were terminated shortly after spark cessation. This behavior was observed for all configurations involving the declared fire retardant foam from Supplier A and for the mattress store polyurethane foam when ignition did not occur. The resulting graphs exhibit short-duration traces with low amplitude, indicating the absence of sustained heat release from the foam.

In contrast, scenarios involving sustained flaming ignition of the mattress store polyurethane foam produced pronounced thermal escalation. Under exposure to the “Silver rain” device, ceiling-level thermocouples recorded progressive temperature increases, with peaks substantially exceeding those measured in the fire-compliant configurations. Under exposure to the “Sputnik” device, the temperature rise was more severe. Figure 26 shows ceiling temperatures approaching or exceeding 800°C, with sustained elevated values during the active combustion phase. Lower-level thermocouples positioned at the mannequin’s hand and chest also registered significant temperature increases during these events, indicating vertical propagation of the thermal field within the compartment.

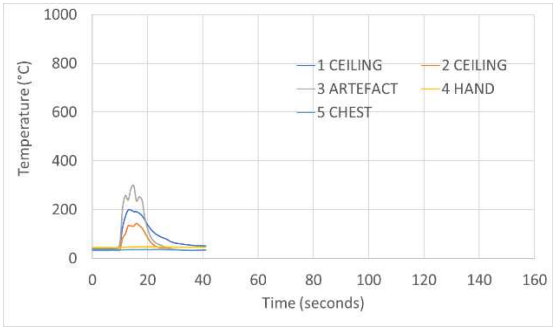


Figure 25 – Temperature, Sputnik X foam from Supplier A

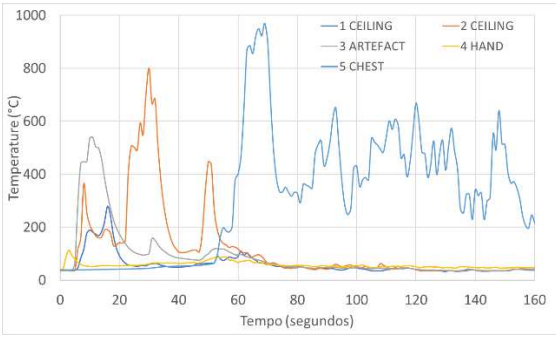


Figure 26 – Temperature, Sputnik X mattress store polyurethane foam

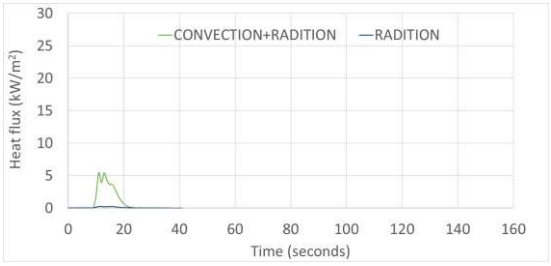


Figure 27 – Heat flux, Sputnik X foam from Supplier A

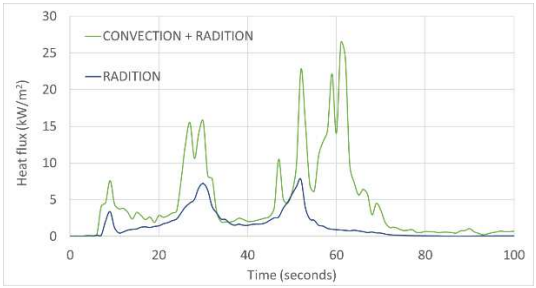


Figure 28 – Heat flux, Sputnik X mattress store polyurethane foam

Heat flux measurements obtained during ignition of the pyrotechnic devices revealed that both artifacts generated relatively low incident heat flux levels when compared to standardized laboratory test exposures. The Sputnik device produced peak heat flux values exceeding 5 kW/m² during its ignition phase, although this transient exposure alone did not immediately result in sustained ignition of the Manufacturer A foam. In contrast, the Silver Rain artifact generated lower peak incident heat flux levels, generally between 1 and 2 kW/m². Despite the lower measured heat flux, Silver Rain could initiate ignition in the mattress-store polyurethane foam configuration. In the reconstruction compartment measurements (Figure 28), the initial heat flux increased to values slightly above 5 kW/m² due to combined radiative and convective contributions before decreasing, preceding the onset of sustained fire growth. These results document the actual thermal exposure imposed by the pyrotechnic sources independently of subsequent fire development.

Heat flux measurements followed a similar pattern. In non-ignition scenarios, recorded flux values remained low and transient. In ignition scenarios involving the mattress store polyurethane foam, combined convective and radiative heat flux measured at approximately two meters above the floor reached values above 20–25 kW/m² (Figure

24 and Figure 28). At approximately one meter above the floor, radiative flux values reached approximately 5 kW/m² during peak combustion periods. These peaks correspond temporally to the periods of maximum flame development observed visually.

The duration of measurements in flaming scenarios extended up to approximately 160 seconds, capturing the full growth and decay phases of the burning single panel. In contrast, non-flaming scenarios were terminated shortly after cessation of visible sparks, resulting in truncated curves.

Under identical geometric and exposure conditions, the measured temperature and heat flux data demonstrate substantial differences in the thermal environment generated by each material. The mattress store polyurethane foam produced the highest temperature peaks, the highest incident heat flux values, and the most sustained thermal exposure.

e) Smoke Production and Visual Obscuration

Qualitative smoke observations were consistent with the thermal escalation patterns described previously and are summarized in Table 2. Sustained flaming of the untreated mattress-store polyurethane foam resulted in rapid formation of a dense upper smoke layer accompanied by significant visual obscuration within the enclosure. In contrast, the declared fire-retardant foam from Supplier A produced only transient emissions associated with the pyrotechnic device, without sustained smoke accumulation.

The intermediate behavior observed for Supplier B occurred only under sustained flaming conditions and remained less severe than that documented for the untreated foam.

It is important to note that the hazard associated with smoke production is strongly influenced by enclosure characteristics. In confined or poorly ventilated occupancies with limited egress capacity, rapid smoke layer formation may critically impair visibility and tenability. In more open or ventilated environments, identical material behavior may produce different exposure outcomes. The present study reports material response within the tested configuration without extending interpretation to evacuation modeling scenarios.

f) Comparative Summary of Observed Behaviors

Under identical geometric and ignition conditions, the three materials exhibited a clear performance gradient. The untreated mattress-store polyurethane foam transitioned rapidly to sustained flaming, showed progressive surface involvement, frequent flaming melt-dripping, and generated the highest temperature and heat flux levels within the enclosure. The declared fire-retardant foam from Supplier B demonstrated intermediate behavior, with sustained ignition occurring under the higher-energy exposure and with reduced thermal intensity and shorter duration compared to the untreated foam.

However, Supplier B was expected, according to the manufacturer’s technical documentation, to exhibit performance comparable to Supplier A under flame exposure conditions. In contrast, the declared fire-retardant foam from Supplier A did not establish sustained flaming under any tested condition and remained limited to localized degradation without significant thermal escalation or secondary ignition phenomena. These observations therefore do not reflect a deliberately selected performance gradient, but rather the experimentally observed divergence between declared and measured behavior.

These full-scale observations provided a rational basis for structuring the subsequent laboratory investigation around the two bounding performance conditions of greatest analytical relevance: the untreated flexible polyurethane foam representative of the material type installed in the Kiss nightclub, and the declared fire-retardant foam from Supplier A, which demonstrated suppression of sustained flaming. Based on the

qualitative similarity in fire response previously discussed, the mattress-store foam was selected as a functionally representative surrogate for the original acoustic foam recovered from the nightclub for detailed laboratory-scale characterization in the following section.

2.3. Laboratory tests with real foam from the Kiss nightclub

This study combined a non-standardized full-scale container reconstruction with standardized laboratory testing to characterize the fire behavior of polyurethane foams relevant to the Kiss nightclub scenario. The container reconstruction served as a screening step to identify the most contrasting materials for subsequent laboratory comparison. Based on the reconstruction outcomes, two materials were selected for laboratory evaluation: (i) the Kiss nightclub foam recovered from the incident scene, representing the worst-performing material in the scenario, and (ii) the declared fire-retardant foam from Supplier A, representing the best-performing material among the evaluated products.

The laboratory program was organized in two stages. First, thermogravimetric analysis (TGA) was performed on both the recovered Kiss foam and the Supplier A foam to compare intrinsic thermal degradation behavior under controlled heating. Second, a standardized NFPA 286 room-corner test was performed exclusively on the recovered Kiss foam by an independent U.S. laboratory, providing compartment-scale heat release and smoke-related measurements under a prescribed room geometry and burner protocol. The purpose of restricting NFPA 286 testing to the recovered Kiss foam was to quantify, under standardized compartment conditions, the behavior of the material directly involved in the incident.

2.3.1. Laboratory Tests Configuration and Specimen Preparation

The recovered Kiss foam consisted of fragmented remnants. Despite this condition, the material was sufficient for laboratory handling when specimen mass requirements were compatible with fragmentary samples, as in thermogravimetric analysis. The Supplier A foam was selected as a comparator because it exhibited the most favorable behavior in the preliminary full-scale container reconstruction, allowing a clear contrast between the poorest and best-performing materials within the study's experimental framework.

TGA was performed on both the recovered Kiss foam and the declared fire-retardant foam from Supplier A to compare intrinsic decomposition characteristics under controlled heating. The analysis aimed to document onset of mass loss, multi-stage degradation behavior, and residual mass fraction, providing a material-level baseline that supports interpretation of the subsequent compartment test results. Thermogravimetric analysis was conducted using a TA Instruments TGA Q500 under controlled heating conditions, with mass variation recorded continuously as a function of temperature.

A full-scale NFPA 286 room-corner test was conducted exclusively on the recovered Kiss foam to quantify its compartment fire behavior under a standardized enclosure configuration. The test was performed by an independent U.S. laboratory specializing in fire testing of interior finish materials. The present study is based on the complete technical report and time-resolved dataset provided by that laboratory. Because the NFPA 286 configuration requires mechanically stable and contiguous lining installation, the test specimens were prepared and installed by the testing laboratory in accordance with the standard's requirements and the laboratory's documented procedures.

2.3.2. Results of Laboratory Tests

a) Thermogravimetric Analysis (TGA) tests

Thermogravimetric analysis was conducted to characterize the intrinsic thermal

degradation behavior of the Kiss acoustic foam and the declared fire-retardant foam from Supplier A under controlled heating conditions. The corresponding mass-loss curves are presented in Figure 29 (Kiss foam) and Figure 30 (declared fire retardant foam from Supplier A).

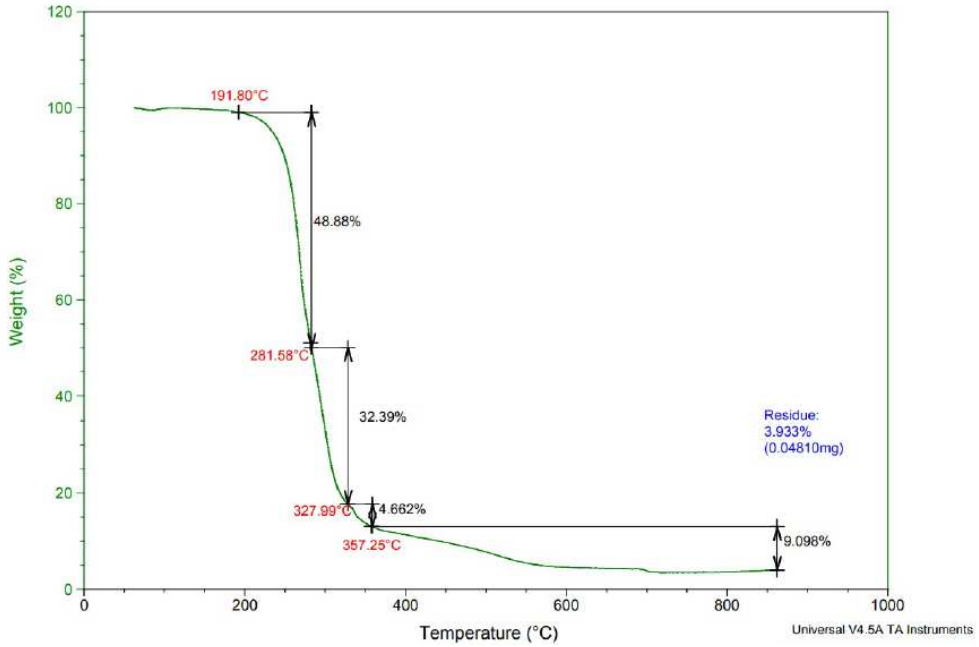


Figure 29 – Thermal degradation of the Kiss acoustic foam [28]

Figure 29 illustrates the mass-loss profile of the Kiss foam as a function of temperature. An initial region of relative thermal stability is followed by a pronounced degradation phase. Significant mass loss begins at approximately 190°C, with rapid decomposition occurring between roughly 200°C and 390°C. Within this temperature interval, the material loses approximately 88% of its initial mass. The steep slope of the curve indicates accelerated volatilization and rapid breakdown of the polymer network once the critical decomposition threshold is exceeded. Beyond approximately 390°C, the remaining mass decreases more gradually, resulting in a minimal residual fraction at the end of the heating cycle. The low final residue suggests limited char formation and a predominance of volatile decomposition products.

In contrast, the declared fire-retardant foam from Supplier A exhibits a distinctly different degradation pattern, as shown in Figure 30. The onset of major mass loss occurs at a higher temperature compared to the Kiss foam. The decomposition process is distributed over multiple stages rather than concentrated in a single abrupt event. The principal degradation interval occurs closer to 300–390°C, and the overall mass-loss progression is less steep. This more gradual reduction in mass indicates delayed thermal breakdown and modified degradation kinetics. The residual mass fraction at elevated temperature is also higher than that observed for the Kiss foam, consistent with enhanced condensed-phase stability.

Comparison of Figure 29 and Figure 30 highlights three principal distinctions. First, the Kiss foam exhibits an earlier onset of significant degradation, while the declared fire-retardant foam maintains structural stability over a broader temperature range prior to major mass loss. Second, the Kiss foam undergoes a sharper and more concentrated degradation phase, indicating faster volatilization once decomposition initiates, whereas the fire-retardant foam degrades in a staged and moderated manner. Third, the residual mass fraction of the Kiss foam is lower at the conclusion of the heating cycle, while the

declared fire-retardant foam retains a comparatively greater residue.

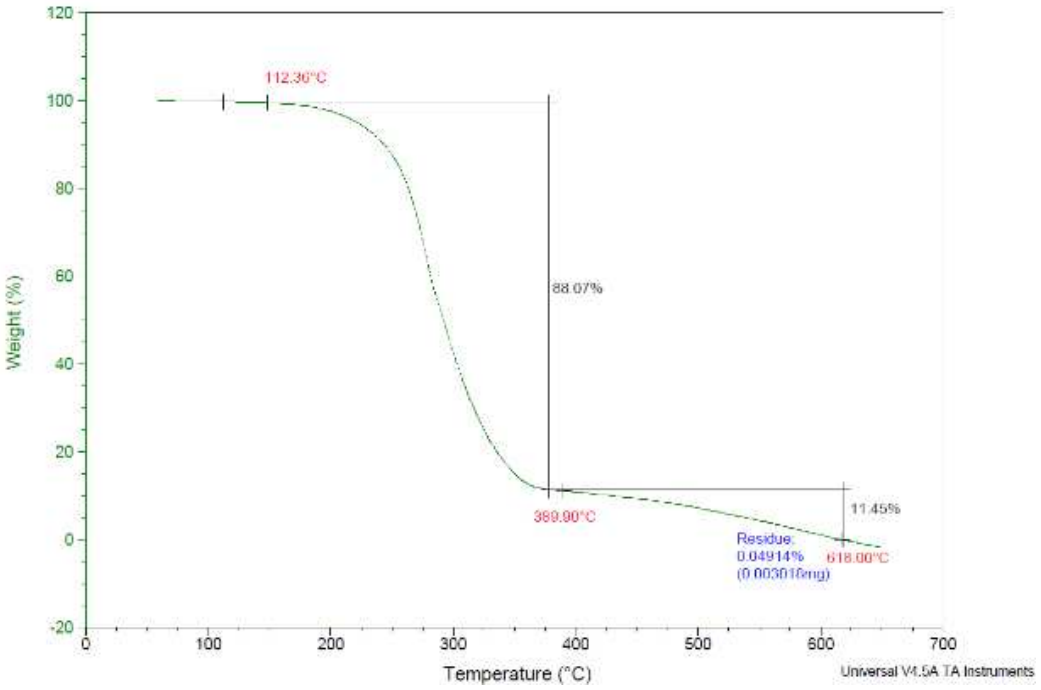


Figure 30 – Declared fire retardant foam from Supplier A [28]

These differences demonstrate distinct intrinsic thermal decomposition behaviors under identical heating conditions. The Kiss foam shows earlier degradation onset and more abrupt mass loss, whereas the declared fire-retardant foam exhibits delayed and distributed thermal breakdown. Although thermogravimetric analysis does not replicate compartment fire conditions, it provides controlled thermochemical data that help interpret the contrasting behaviors observed during the NFPA 286 room-corner experiments. In particular, earlier degradation and limited residue formation are consistent with a greater availability of combustible volatiles during the initial stages of heating.

Given the central role of the acoustic foam in the fire origin scenario, subsequent laboratory analysis focuses primarily on the Kiss foam. Greater analytical emphasis is therefore placed on detailed characterization of the intrinsic thermochemical and combustion properties of the material directly involved in the incident, in order to clarify its contribution to early fire development and overall fire severity. The declared fire-retardant foams from Suppliers A and B were not subjected to further detailed laboratory characterization beyond the analyses presented, as their performance in the NFPA 286 configuration and their thermogravimetric profiles were considered sufficient for comparative purposes within the defined scope of this study.

b) Standardized Full-Scale Compartment Test: NFPA 286 Room Corner Test

The NFPA 286 Room Corner Test was conducted to characterize the compartment-scale fire development of the Kiss nightclub flexible polyurethane foam under standardized full-scale conditions. Testing was performed by an independent U.S. laboratory specialized in fire performance evaluation of interior finish materials. The burner exposure protocol, instrumentation layout, exhaust hood calorimetry system, and data acquisition

procedures were executed in accordance with NFPA 286. The present analysis is based on the complete technical report [29] and the original time-resolved dataset supplied by the testing laboratory.

Unlike small-scale material tests, NFPA 286 captures enclosure feedback effects, flame spread across vertical and overhead surfaces, and the interaction between heat release, gas accumulation, and ventilation within a defined room geometry. The following sections describe the temporal evolution of ignition, fire growth, heat release, smoke production, and gas-phase composition observed during the test.

Early Fire Development

The test was conducted in a standardized room enclosure equipped with a corner ignition burner and an exhaust hood calorimetry system based on oxygen consumption. Figure 31 presents the measured heat release rate as a function of time.

Ignition was initiated by the prescribed propane burner positioned in the rear corner of the compartment, providing a controlled and reproducible thermal exposure representative of a developing enclosure fire. Sustained flaming of the lining was observed during the early phase of burner exposure (approximately 72 s after test initiation). This time value does not represent a material time-to-ignition parameter as defined in bench-scale calorimetry, but rather the observed transition from burner-dominated heating to lining-dominated combustion under compartment conditions. Once sustained combustion was established, flame propagation across the exposed lining surface progressed rapidly. No evidence of self-extinguishment or delayed re-ignition was recorded during the growth phase.

Following this transition, the HRR curve exhibits a steep ascending branch, culminating in a peak at approximately 167 s. The short interval between sustained ignition and peak HRR characterizes a rapid early growth phase, with substantial fuel involvement occurring within the first three minutes of exposure.

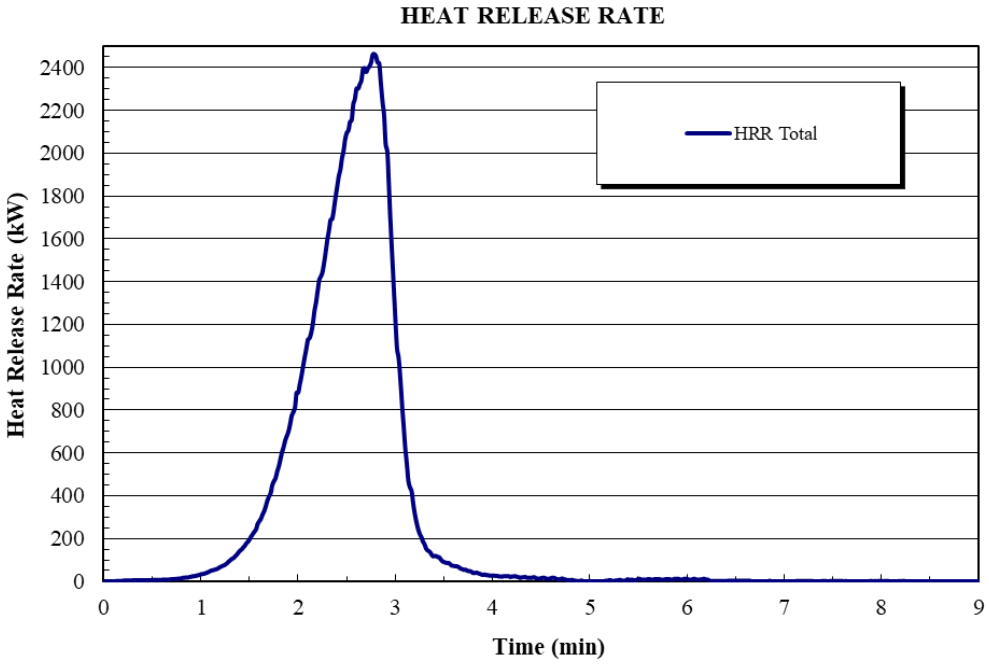


Figure 31 – HRR of the Kiss acoustic foam [29]

After reaching peak heat release, the measured heat release rate decreased abruptly. No sustained steady-burning plateau was observed during the post-peak phase. The

decline in heat release is consistent with progressive reduction of combustible material involvement and structural degradation of the foam lining within the compartment configuration.

Following this transition, the HRR curve exhibited a steep ascending branch that indicates the early fire development behavior of the tested flexible polyurethane foam under NFPA 286 room-scale conditions. Quantitative evaluation of peak heat release, total heat released, smoke production, and combustion gas composition is presented in the following sections.

Heat Release Rate (HRR) behavior

The heat release rate (HRR) curve obtained under NFPA 286 room-corner conditions is presented in Figure 31. The measurements were derived from oxygen consumption calorimetry in the exhaust duct and represent the total heat release from the compartment lining system, excluding the calibrated contribution of the propane burner as reported in the test documentation.

The foam configuration reached a peak heat release rate (pHRR) of 2465.33 kW at 2.783 minutes from the start of the test. The ascending branch of the curve shows rapid acceleration following sustained ignition of the lining material, culminating in a sharp and clearly defined maximum. No secondary peak of comparable magnitude was recorded during the test duration.

After reaching peak heat release, the HRR decreased abruptly. The post-peak phase did not exhibit an extended steady-burning plateau. Instead, combustion intensity declined progressively as material involvement decreased and visible flaming intensity diminished within the compartment. Heat release approached near-baseline levels within approximately four minutes after test initiation.

The total heat released over the duration of the test was 142 MJ, as determined by the duct-based oxygen consumption calorimetry system. This cumulative energy output reflects the integrated contribution of the foam lining under the prescribed burner exposure and ventilation conditions of the NFPA 286 configuration.

The HRR profile demonstrates a strong concentration of heat release in the early stage of compartment involvement. A substantial portion of the total energy was liberated within the first three minutes, corresponding to the interval between sustained ignition and the onset of rapid decay. The absence of a prolonged steady-burning plateau reflects the transient nature of the compartment heat release profile under the prescribed NFPA 286 exposure conditions.

These quantitative HRR parameters provide the foundation for the subsequent evaluation of smoke production, combustion gas evolution, and fire growth characteristics under room-scale conditions.

Smoke Release Rate and Optical Density test

Smoke production under NFPA 286 room-corner conditions is presented in Figure 32 and summarized in the test results table. The measurements were obtained using duct-based instrumentation integrated into the room-corner exhaust system and include instantaneous smoke release rate (SPR), cumulative total smoke released (TSR), and optical density derived from light attenuation across the exhaust stream during combustion.

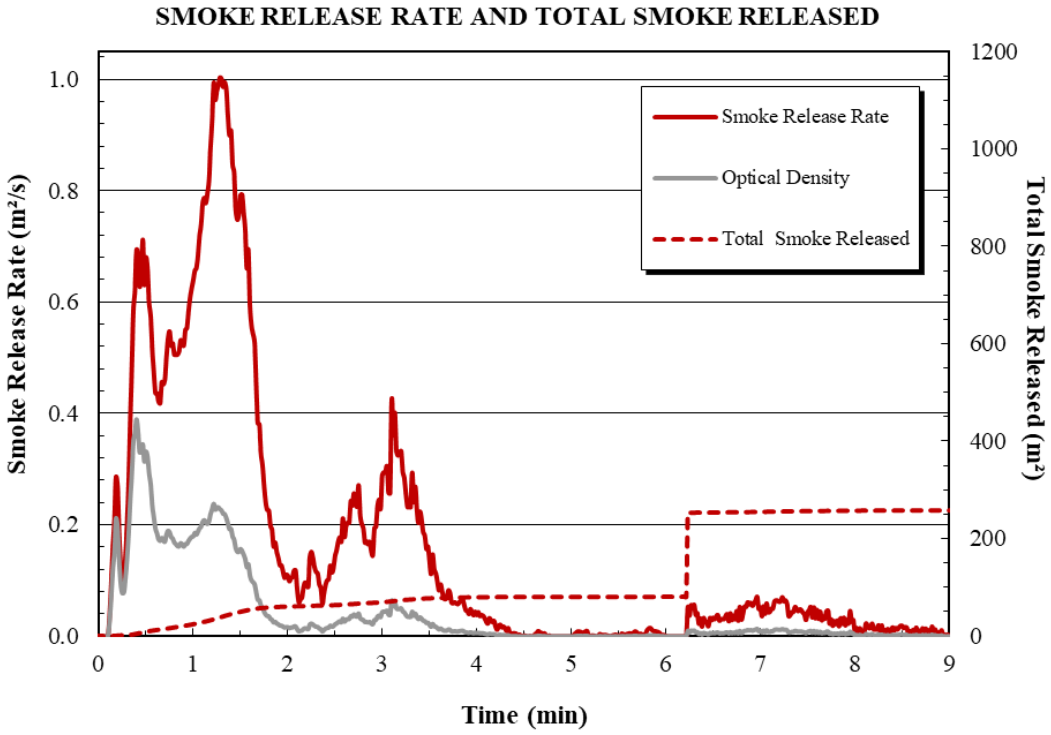


Figure 32 – Thermal degradation of the Kiss fire-retardant foam [29]

The maximum smoke release rate was 1.00 m²/s, occurring at 1 minute and 17 seconds after test initiation. This peak developed during the early growth phase identified in the corresponding heat release curve. As the measured HRR decreased following the peak phase, the SPR declined accordingly. The average smoke release rate over the test duration was approximately 0.29 m²/s.

The cumulative smoke production reached 259 m² over the duration of the test. The TSR curve shows a steep increase during the initial growth interval, followed by a reduced rate of accumulation as combustion intensity diminished.

Optical density measurements quantify the light attenuation characteristics of the exhaust gases. The maximum optical density reached 0.39 m^{-1} at 24 seconds, while the average optical density over the test duration was 0.035 m^{-1}. The maximum optical density occurred prior to the peak in total heat release.

The combined SPR, TSR, and optical density results provide quantitative descriptors of smoke generation and obscuration under compartment-scale exposure conditions. The reported values correspond directly to the exhaust duct measurements obtained during the NFPA 286 test configuration.

Gas Emissions and Oxygen Depletion

Gas concentrations were continuously monitored during the NFPA 286 room-corner test. The measured species included carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) mole fractions as functions of time. Figure 33 presents the temporal variation of CO and CO_2 concentrations in the exhaust stream, and Figure 34 shows the corresponding O_2 concentration profile.

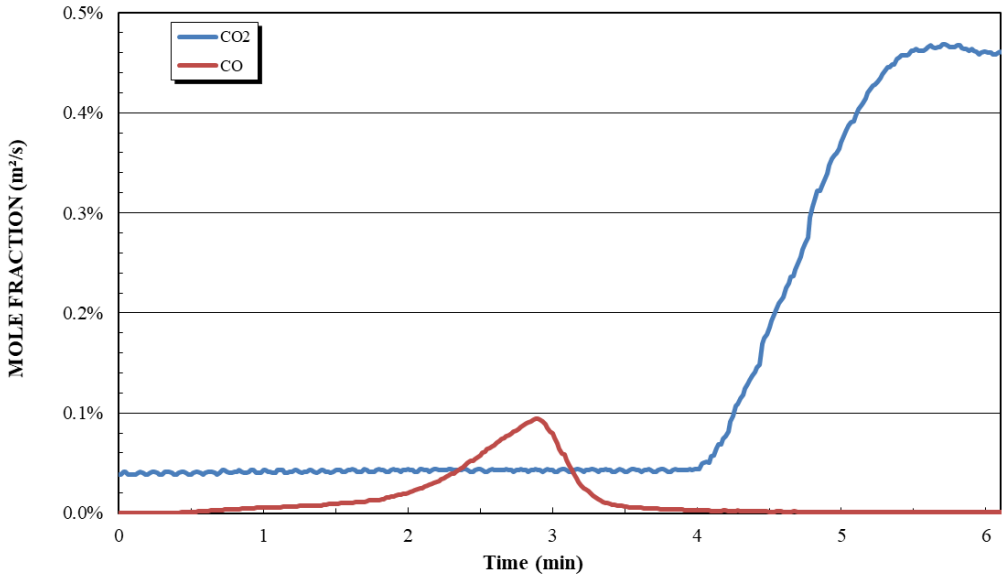


Figure 33 – Gasometry (CO_2 and CO) of the real Kiss Nightclub foam under fire conditions[31]

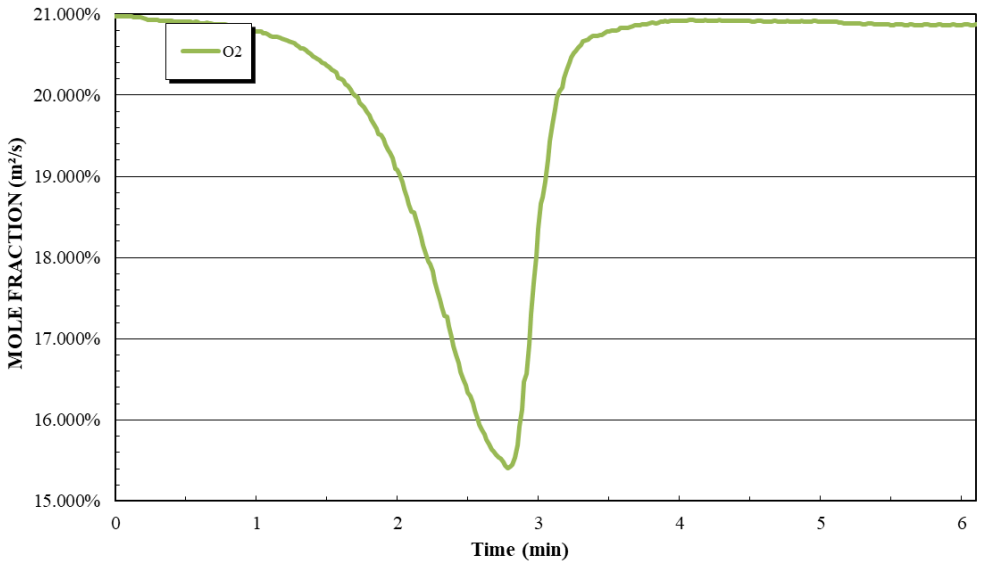


Figure 34 – Gasometry (O_2) of the real Kiss Nightclub foam under fire conditions[31]

The CO_2 concentration increased following burner exposure and material involvement, reaching a maximum measured value of approximately 0.48% (mole fraction). The maximum CO_2 value occurred during the period of elevated heat release within the compartment.

Carbon monoxide exhibited a maximum measured value of approximately 0.089% (mole fraction) at approximately 2 min 47 s from the start of the test. This maximum occurred during the interval of highest recorded heat release rate. Following this peak, CO concentration decreased progressively as the measured heat release rate declined.

Oxygen concentration decreased from an ambient baseline of approximately 21.0% to a minimum measured value of approximately 15.43% at approximately 2 min 47 s, corresponding temporally to the period of maximum heat release rate. After reaching this minimum, O_2 levels increased progressively as total heat release decreased.

The temporal alignment between maximum CO concentration, minimum O_2 concentration, and peak heat release rate reflects the period of highest combustion intensity recorded during the test. The reported gas concentrations correspond directly to the exhaust duct measurements obtained during the NFPA 286 room-corner configuration.

No additional gas species were reported in the laboratory dataset beyond CO, CO_2, and O_2. The gas emission results presented here therefore correspond exclusively to these measured combustion products under the specified test conditions.

3. Discussion

3.1. Functional Representativeness of the Tested Foams

A central methodological distinction in this study concerns the use of two different experimental configurations: a non-standardized full-scale container reconstruction and a standardized NFPA 286 room-corner test. Each configuration served a distinct purpose and therefore required different material allocation strategies.

The non-standardized reconstruction test was designed to reproduce the documented ignition mechanism and installation geometry associated with the Kiss nightclub fire. Investigative records indicate that the original stage lining consisted of flexible polyurethane foam manually cut from mattress retail stock, acquired without certification or declared fire performance classification. In order to replicate this procurement pathway and installation condition, a commercially available mattress-store polyurethane foam was used in the reconstruction phase. The selection was intentional and scenario-driven: the objective was to reproduce the real acquisition process and ceiling-mounted configuration rather than to establish standardized performance metrics.

The use of this retail foam in the reconstruction context was methodologically justified. Representativeness in reconstruction experiments is functional and scenario-based. The relevant criterion is not chemical identity but equivalence in material category, installation geometry, and ignition exposure. Untreated, non-certified flexible polyurethane foam purchased through the same commercial pathway reflects the documented risk context of the original event. Within the defined reconstruction objective, the surrogate material provided a valid platform to observe ignition behavior, flame attachment, and qualitative fire development under pyrotechnic exposure.

In parallel, material allocation was managed conservatively to preserve the maximum possible quantity of recovered Kiss nightclub foam for standardized testing. The NFPA 286 room-corner experiment was performed using the recovered Kiss foam itself. This test provided the quantitative compartment-scale performance data reported in this study, including heat release rate, total heat released, smoke production, and gas evolution under a prescribed burner protocol. The standardized NFPA 286 results therefore correspond directly to the original material involved in the incident.

The separation of material use between the two experimental phases was deliberate. The reconstruction test addressed scenario reproduction under non-parametrized conditions using a functionally equivalent retail foam. The NFPA 286 test provided standardized, quantitative compartment fire performance metrics for the recovered Kiss foam. This allocation strategy preserved specimen integrity for the most controlled and analytically rigorous phase while maintaining scenario fidelity in the reconstruction phase.

Within these defined boundaries, the mattress-store foam is representative for reconstruction purposes, and the NFPA 286 results are representative of the recovered Kiss nightclub material under standardized compartment exposure. No claim of chemical

identity is made between materials, and no standardized performance metrics are derived from the reconstruction test. Each dataset is interpreted within its appropriate experimental context.

Investigative records indicate that the stage lining consisted of flexible polyurethane foam manually cut from mattress retail stock, without certification, declared fire classification, or documented flame-retardant treatment. The surrogate foam used in this study (reconstruction test) was obtained through an equivalent commercial pathway: retail mattress supply, absence of declared flame-retardant additives, and no manufacturer-issued fire performance documentation. This procurement condition is not incidental. It reflects the absence of regulatory control over material selection that formed part of the original risk context.

3.2. Fire Growth and Combustion Behavior of the Kiss Foam under NFPA 286 Conditions

The untreated foam exhibited a rapid transition from burner-controlled heating to material-dominated combustion. Sustained involvement of the ceiling-mounted lining occurred shortly after burner application, and the heat release rate increased steeply, reaching a peak of 2465 kW at approximately 167 s. This magnitude substantially exceeds the 800 kW criterion referenced in Annex C.2 of NFPA 286 for acceptable interior finish performance. From a regulatory standpoint, the material does not satisfy this peak heat release threshold.

The short interval between sustained ignition and peak output indicates accelerated fire growth within the compartment. Once flaming was established on the ceiling surface, the foam acted as a significant secondary fuel source, intensifying enclosure combustion during the first three minutes of exposure. In compartment fire dynamics, such behavior is associated with rapid generation of combustible gases, strong thermal feedback from the developing upper hot gas layer, and enhanced flame spread along overhead surfaces. The measured evolution of heat release is therefore consistent with a thermally thin, high-fuel-content lining subjected to localized ignition in a confined geometry.

The total heat released during the test was 142 MJ. Although NFPA 286 acceptance criteria emphasize peak heat release rather than cumulative energy alone, the magnitude of the measured THR confirms substantial energetic contribution from the lining within a limited time window. The heat release curve did not exhibit a prolonged quasi-steady plateau following the peak. Instead, combustion intensity declined relatively rapidly, consistent with progressive consumption, melting, and reduction of exposed combustible surface area. Flexible polyurethane foams typically form limited thermally stable residue under flaming conditions, and the observed post-peak decay is coherent with this material behavior.

The temporal concurrence of peak heat release, maximum carbon monoxide concentration, and minimum oxygen concentration indicates that the most severe combustion conditions occurred within the same interval. As heat release intensified, oxygen concentration in the enclosure decreased and incomplete combustion products increased, reflecting elevated oxidation demand and ventilation interaction. These coupled trends confirm that the peak phase represented a period of high fuel conversion rate and significant enclosure impact.

Thermogravimetric analysis of recovered foam fragments showed early onset of degradation, rapid mass loss, and minimal residual fraction. However, differences in thermal decomposition curves between the Kiss foam and a declared fire-retardant product were less pronounced than the distinctions observed under NFPA 286 conditions. This divergence highlights the distinction between isolated thermal

degradation in small specimens and flaming combustion in a ventilated enclosure. In the compartment test, flame spread over installed surfaces, heat feedback from the hot gas layer, and ventilation-controlled oxidation govern fire growth. Under such conditions, relatively modest differences in decomposition behavior can translate into substantial differences in peak heat release and enclosure response.

Taken together, the measured peak heat release of 2465 kW, the rapid time to peak, and the total energy discharge define a fire growth pattern characterized by concentrated early energy release and strong compartment involvement. Within the defined NFPA 286 geometry and burner protocol, the untreated foam demonstrates a level of fire growth severity that exceeds the Annex C.2 performance criterion for peak heat release. This conclusion is configuration-specific and limited to the tested installation, but within those boundaries, the material exhibits combustion behavior consistent with accelerated enclosure fire development once ignition is achieved.

3.3. Smoke Production and Tenability Indicators

Smoke production and gas composition were measured during the NFPA 286 Room Corner Test through analysis of the exhaust stream, under the same compartment configuration used to determine heat release rate. In this setting, smoke and gas generation cannot be interpreted independently of fire growth. They are direct consequences of the rate of fuel generation, the ventilation regime within the enclosure, and the evolving balance between complete and incomplete oxidation. For this reason, the discussion below is framed in relation to the heat release behavior described in Section 3.2.

The untreated foam produced a peak smoke release rate of 1.00 m^2/s at approximately 77 s, preceding the peak heat release rate at 167 s. This chronology indicates that intense particulate generation began during the early growth phase, before the enclosure reached its maximum thermal output. In ceiling-mounted flexible polyurethane, rapid surface heating and volatilization produce hydrocarbon-rich gases that favor soot formation under dynamically changing ventilation conditions. The early smoke peak is therefore consistent with the transition from localized ignition to developing compartment involvement.

The cumulative smoke production, expressed as total smoke released, reached 258.8 m^2. Annex C.2 of NFPA 286 references a threshold of 1000 m^2 for acceptable performance. On this basis, the tested material satisfies the TSR criterion. This result contrasts with the failure of the 800 kW peak heat release requirement discussed in Section 3.2. The combined outcome illustrates that smoke quantity and heat release intensity are not necessarily proportional in regulatory terms. While the total integrated smoke output remained below the acceptance limit, the energy release rate was sufficiently high to exceed the prescribed HRR criterion. From a hazard perspective, the material demonstrates limited cumulative smoke relative to the code threshold but exhibits severe early fire growth.

Optical density reached a maximum of 0.389 m^{-1} at approximately 24 s, substantially earlier than the heat release peak. This early obscuration confirms that visibility impairment developed rapidly once flaming was established. In a confined enclosure, light attenuation during the growth phase can precede peak thermal conditions, affecting tenability before maximum heat release is attained. The temporal alignment between early optical density increase and early smoke release rate peak reinforces the interpretation of pronounced initial soot production under ceiling-level burning.

Gas concentration trends further characterize the combustion regime. Carbon monoxide reached a maximum concentration of 0.089% at 167 s, coincident with peak heat

release, while oxygen concentration decreased from ambient levels to a minimum of 15.43% at the same time. This concurrence indicates that the most intense combustion phase was also associated with the highest oxygen demand and elevated incomplete oxidation. In oxygen-consumption calorimetry, such coupling is expected: increased heat release reflects increased fuel oxidation, which reduces available oxygen and can promote carbon monoxide formation under transient ventilation constraints.

Carbon dioxide reached a maximum of 0.48% slightly after the heat release peak. This delayed maximum is consistent with continued oxidation of intermediate combustion products during the post-peak phase. As fuel generation declines and mixing conditions evolve, conversion of carbon monoxide and other intermediates to carbon dioxide becomes more pronounced, shifting the gas composition during the decay period.

When considered together, these measurements describe a coherent compartment-scale combustion sequence: early smoke generation and visibility degradation; rapid escalation to a high peak heat release exceeding 800 kW; simultaneous oxygen depletion and carbon monoxide formation at maximum fire intensity; and continued carbon dioxide production during decay. Although the total smoke released remained below the 1000 m² criterion, the combined heat release magnitude and early tenability impacts indicate a lining capable of producing severe enclosure conditions once ignition is achieved.

3.4. Thermal Exposure and Secondary Mechanisms

The full-scale reconstruction experiments provide direct measurements of the thermal environment generated by sustained combustion of untreated flexible polyurethane foam under localized pyrotechnic ignition. Unlike inferred scenarios based solely on heat release rate, these tests quantified temperature and incident heat flux within the enclosure, allowing direct evaluation of tenability conditions and injury potential.

3.4.1. Thermal Exposure: Temperature–Heat Flux Interaction

Assessment of thermal injury in enclosure fires requires simultaneous consideration of gas temperature and incident heat flux. Air temperature alone does not determine tissue damage or clothing ignition. Radiative and convective heat flux govern energy transfer to exposed surfaces and therefore define the severity of exposure. The full-scale reconstruction measurements obtained in this study allow direct comparison with established tenability criteria.

During sustained burning of the untreated mattress-store foam installed in the ceiling configuration, upper-layer gas temperatures approached approximately 800°C. Concurrently, combined convective–radiative heat flux measured at approximately 2 m above floor level exceeded 20–25 kW/m². At approximately 1 m height, radiative flux alone reached values near 5 kW/m². These values were recorded under partially ventilated conditions and with limited fuel surface area.

These magnitudes exceed established human tolerance thresholds. According to Braga et al. [32] and Foster and Roberts [33], exposure above approximately 100°C and 1 kW/m² is beyond routine firefighter operating conditions. The exposure map reproduced in Figure 35 classifies combinations near 200°C and 4 kW/m² sustained for one minute as extreme conditions. The measured upper-layer temperatures and fluxes in the present experiments substantially exceed those combinations.

The skin tolerance diagram shown in Figure 36 further contextualizes the radiative component. Radiant exposure near 4 kW/m² may produce blistering under sustained exposure, whereas flux levels approaching 10 kW/m² reduce time to blister formation to seconds. NFPA 921 [13] and the SFPE Handbook [14] similarly identify approximately 1

kW/m² as a pain threshold, 4 kW/m² as a blister threshold under continued exposure, and values near 10 kW/m² as capable of causing blistering within seconds. Fluxes approaching 20–25 kW/m² fall within a regime associated with rapid burn injury and potential clothing ignition. The enclosure conditions measured in this study therefore lie well within injury-producing ranges according to multiple independent references.

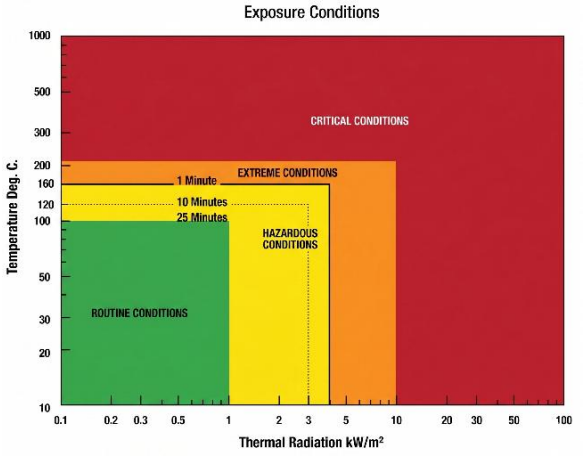


Figure 35 – Exposure conditions of thermal radiation and temperature [32][33]

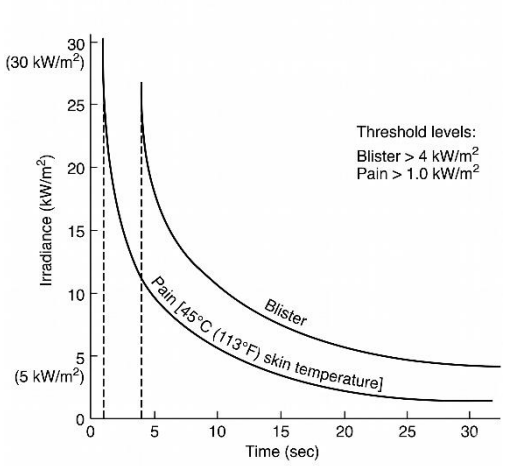


Figure 36 – Diagram Showing Incident Radiant Heat Flux Effect on Bare Skin [3]

It is relevant that these exposures were generated by combustion of a single foam panel. In the Kiss nightclub, substantially larger areas of foam were reportedly installed on walls and ceiling elements, and mechanical ventilation was operating during early fire development. Under such circumstances, cumulative heat release and upper-layer heat flux would be expected to increase with burning area and ventilation-driven combustion intensity. The present measurements therefore demonstrate that even limited untreated foam coverage can generate severe thermal environments once ignition is achieved.

Importantly, these values were obtained from combustion of a single foam panel in a partially ventilated configuration. In the Kiss nightclub, substantially larger surface areas of foam were installed on walls and ceiling elements, and mechanical ventilation reportedly operated during early fire development. Under such conditions, cumulative heat release and upper-layer heat flux would be expected to scale with burning area and ventilation, increasing the likelihood of rapid development of untenable thermal conditions.

3.4.2. Ignition Sensitivity under Low Incident Heat Flux

Heat flux measurements during ignition of the pyrotechnic devices provide insight into ignition vulnerability. The Sputnik device produced peak incident heat flux values exceeding approximately 5 kW/m² during its ignition phase, whereas the Silver Rain device generated lower peak fluxes generally between 1 and 2 kW/m². Despite these comparatively modest exposure levels, sustained flaming ignition occurred in the untreated polyurethane foam configuration.

In the compartment measurements, the initial combined radiative and convective flux slightly exceeded 5 kW/m² prior to sustained fire growth. These findings demonstrate that localized ignition sources delivering flux levels on the order of only a few kilowatts per square meter were sufficient to initiate flaming combustion in the untreated foam.

The standard NFPA 286 burner protocol involves defined heat release levels corresponding to substantially higher thermal input than the incident flux generated by the pyrotechnic devices alone. This comparison does not suggest inadequacy of the

standard. Rather, it highlights that certain flexible polyurethane foams may ignite and transition to sustained burning under thermal exposures lower than those typically associated with standardized ignition scenarios. In stage environments where pyrotechnics are used in close proximity to combustible linings, such sensitivity represents a relevant risk mechanism.

The experimental evidence therefore supports a scenario in which relatively low radiant flux, when applied directly to ceiling-mounted untreated foam, is sufficient to initiate fire growth that subsequently becomes material-driven and enclosure-amplified.

3.4.3. Flaming Melt-Dripping and Secondary Hazard Pathways

Sustained combustion of the untreated foam was accompanied by flaming melt-dripping. Molten droplets detached while burning and produced localized temperature spikes exceeding 400°C at peripheral thermocouples and approaching 900°C at the chest-level sensor of the instrumented mannequin. These transient spikes occurred independently of the global upper-layer temperature profile.

Burning polyurethane melt-flow is recognized in fire investigation literature as capable of sustaining localized flaming and igniting secondary fuels upon contact. The observed behavior in the present tests confirms this mechanism under compartment conditions. Two distinct hazard pathways arise.

First, flaming droplets falling onto combustible substrates may initiate new ignition points remote from the original ceiling-level involvement. This process can accelerate fire spread across horizontal surfaces and increase the number of active flaming regions within the enclosure.

Second, direct contact between burning molten polymer and exposed skin or clothing represents an injury mechanism independent of ambient air temperature and background heat flux. Localized droplet impingement can produce severe burns even when overall enclosure conditions have not yet reached peak thermal intensity.

Reaction-to-fire classification systems in some jurisdictions explicitly address flaming droplets as a performance parameter. Although such classifications were not the focus of the present study, the observed dripping behavior would be relevant under criteria that consider flaming particle generation.

Within assembly occupancies, flaming melt-dripping adds instability to occupant response. Sudden localized pain or ignition of clothing can disrupt evacuation behavior and increase panic potential. While evacuation modeling was not performed here, the physical mechanisms were directly observed and quantified.

3.4.4. Integrated Interpretation of Full-Scale Findings

The full-scale reconstruction results establish four experimentally supported observations. Sustained burning of untreated flexible polyurethane foam in a ceiling configuration generated upper-layer temperatures approaching 800°C and combined convective–radiative heat flux exceeding 20–25 kW/m². These exposure levels exceed documented human tenability thresholds and fall within rapid injury regimes according to established fire engineering references, as illustrated in Figure 35 and Figure 36.

Flaming ignition occurred under incident heat flux levels on the order of 1–5 kW/m² from pyrotechnic sources, demonstrating sensitivity to relatively low localized thermal exposure.

Combustion was accompanied by flaming melt-dripping capable of producing secondary ignition and localized high-temperature contact hazards.

Taken together, these findings provide a quantitative link between material combustion

behavior and the development of injury-producing thermal environments in assembly occupancies. The interpretation remains confined to the tested geometry, ventilation, and fuel coverage. Within those boundaries, the results demonstrate that untreated flexible polyurethane foam installed on ceiling surfaces can generate severe enclosure conditions once ignition is achieved, even when the initiating heat flux is comparatively modest.

3.5. Regulatory Performance and Scenario-Dependent Interpretation

The NFPA 286 results provide a quantitative basis for evaluating the regulatory performance of the tested untreated flexible polyurethane foam when installed as a ceiling lining in a compartment configuration. Under the conditions of the room-corner protocol, the material exhibited a peak heat release rate of 2465 kW at approximately 167 s and a total smoke released of 258.8 m². These values allow direct comparison with the performance criteria referenced in Annex C.2 of NFPA 286 and adopted by model codes such as NFPA 101, NFPA 5000, the IBC, and the IFC.

Two quantitative observations are immediately relevant. First, the measured peak heat release rate substantially exceeds the 800 kW criterion identified in Annex C.2. Second, the measured total smoke released remains well below the 1000 m² threshold. The material therefore fails the peak heat release criterion while satisfying the total smoke criterion. This divergence requires technical interpretation rather than a binary conclusion.

Peak heat release rate governs the rate at which thermal energy is introduced into the enclosure. In the present test, the rapid escalation to approximately 2.47 MW within less than three minutes indicates accelerated transition from burner-controlled ignition to material-dominated compartment involvement. Under enclosure conditions, such a magnitude of heat release directly influences upper-layer temperature rise, radiative feedback to the lining surface, oxygen consumption, and the rate of tenability loss. The recorded upper-layer temperatures approaching 800°C and incident heat flux in the 20–25 kW/m² range during sustained burning are physically consistent with this level of thermal output. From a regulatory standpoint, exceedance of the 800 kW criterion signals a fire growth severity that is not compatible with the performance intent of the Annex C.2 guidance.

In contrast, the total smoke released of approximately 259 m² is significantly below the 1000 m² threshold. This indicates that, over the duration of the test, the cumulative smoke yield remained within the bounds considered acceptable under the referenced criterion. The apparent contradiction between high heat release and moderate total smoke can be explained by the temporal concentration of combustion. The heat release curve was characterized by a sharp rise to a single pronounced peak followed by decline, rather than by prolonged steady burning. As a cumulative parameter, total smoke integrates both burning intensity and duration. A material capable of generating very high instantaneous heat release over a limited time interval may still produce a total smoke value below a threshold that was established to control extended smoke accumulation. Compliance with the TSR criterion therefore does not offset the implications of the excessive peak heat release.

This outcome illustrates the limits of single-parameter approval logic. Fire behavior in compartments is governed by coupled thermal and chemical processes that evolve continuously rather than categorically. A reduction in peak heat release rate

proportionally reduces the rate of temperature rise and radiative feedback, thereby increasing available safe egress time. Conversely, a substantial exceedance of the peak heat release threshold accelerates enclosure involvement even if cumulative smoke remains below a prescribed limit. In high-occupancy assembly environments, where egress time margins are narrow, the rate of energy release becomes particularly consequential.

The present results also reinforce the scenario-dependent nature of material suitability. In occupancies with limited surface coverage, low occupant density, and robust ventilation, a given level of heat release may not produce catastrophic consequences. In contrast, in an assembly occupancy with extensive ceiling and wall coverage of combustible foam, confined geometry, and high occupant load, the same combustion characteristics amplify hazard. Rapid early heat release shortens the interval between localized ignition and untenable upper-layer conditions. Elevated oxygen consumption and concurrent carbon monoxide formation during the peak heat release interval further degrade tenability. Flaming melt-dripping, observed during sustained burning, introduces additional ignition and injury mechanisms not captured by heat release or smoke metrics alone.

The regulatory significance of the NFPA 286 findings therefore lies not in the invalidation of existing standards, but in the clarification of their application. Annex C.2 criteria are intended to control enclosure fire growth and smoke development. In this case, the material's failure to meet the 800 kW peak heat release criterion indicates a fire growth severity inconsistent with the performance objective of limiting rapid compartment involvement. The fact that the total smoke released remains below 1000 m² does not negate this conclusion, because the primary driver of early tenability loss in the tested configuration was the intensity and rate of energy release rather than cumulative smoke production alone.

Among the measured parameters, heat release rate occupies a central position because it drives multiple secondary phenomena. The temporal coincidence between peak heat release, minimum oxygen concentration of 15.43%, and maximum carbon monoxide concentration of 0.089% confirms that combustion intensity governed gas-phase composition within the enclosure. Increased heat release elevated oxidative demand, reduced available oxygen, and promoted incomplete combustion. Smoke production and optical density development were temporally linked to the growth phase preceding and accompanying the peak. These interdependencies demonstrate that the exceedance of the peak heat release criterion has broader implications for tenability than a single numerical comparison might suggest.

Full-scale compartment testing provides essential context for this interpretation. The NFPA 286 configuration captures enclosure feedback, ceiling flame spread, ventilation interaction, and secondary mechanisms such as flaming dripping. The ignition experiments demonstrated sustained flaming under incident heat flux on the order of 1–5 kW/m² from pyrotechnic sources, followed by enclosure amplification. This sequence highlights the coupling between ignition sensitivity and rapid fire growth once the lining becomes involved. Regulatory evaluation that considers only cumulative smoke or isolated ignition metrics would not fully represent this coupled behavior.

In summary, the tested untreated flexible polyurethane foam exhibits combustion characteristics that are incompatible with the peak heat release performance objective referenced in Annex C.2 of NFPA 286, while satisfying the total smoke released threshold. The dominant regulatory implication arises from the excessive peak heat

release and its associated acceleration of enclosure fire growth. In high-occupancy assembly contexts, such behavior corresponds to rapid thermal escalation, oxygen depletion, and early tenability loss. A technically coherent regulatory assessment must therefore prioritize the rate and magnitude of energy release within the compartment, while recognizing that cumulative smoke compliance does not by itself ensure acceptable fire growth performance.

3.6. Study Limitations and Boundaries of Interpretation

The present investigation combined laboratory characterization and full-scale compartment testing to evaluate the combustion behavior of untreated flexible polyurethane foam under a scenario representative of the Kiss nightclub fire. Although the experimental program was designed to address key aspects of ignition, fire growth, smoke production, and enclosure response, several limitations must be explicitly acknowledged.

First, the room corner experiments were conducted under the geometry, ventilation configuration, and burner protocol prescribed by NFPA 286. While this method captures enclosure feedback and ceiling flame spread under controlled conditions, it represents a standardized test configuration rather than a parametric reconstruction of the original nightclub environment. The room dimensions, ventilation openings, burner power sequence, and installed fuel area were defined by the test standard. Consequently, the measured heat release rate, smoke production, and gas concentrations reflect the interaction between the tested lining and the specific NFPA 286 enclosure, not a full architectural replication of the Kiss nightclub.

Second, not all foam types were subjected to identical suites of testing across all scales. The recovered fragments from the Kiss nightclub were analyzed in laboratory characterization procedures but were structurally unsuitable for installation as ceiling linings in the NFPA 286 configuration. The surrogate retail foam was therefore selected to reproduce the documented procurement pathway and untreated condition of the original installation. While this approach supports functional representativeness, it does not establish chemical identity. Variations in density, additive content, or manufacturing process may exist between batches. The conclusions are therefore limited to untreated flexible polyurethane foams of comparable category and installation geometry, rather than to a single proprietary formulation.

Third, the study did not include testing under additional standardized reaction-to-fire methods such as ASTM E84, ISO 5660, or other bench-scale calorimetric configurations. The experimental emphasis was placed on full-scale enclosure behavior under NFPA 286 conditions, given the scenario-driven objective of evaluating ceiling lining contribution under localized ignition. Inclusion of multiple additional standardized tests for all materials would have substantially increased experimental scope, cost, and manuscript length. The absence of such tests does not invalidate the present findings, but it limits direct cross-comparison with classification systems based on alternative methodologies.

Fourth, the ignition experiments using pyrotechnic devices were conducted to evaluate incident heat flux and ignition sensitivity in a scenario-relevant context. These experiments were not intended as standardized ignition resistance tests. Heat flux measurements from the Sputnik and Silver Rain artifacts demonstrated that sustained flaming could occur under incident flux levels on the order of 1–5 kW/m². These

observations illustrate vulnerability under realistic stage conditions but should not be interpreted as a formal determination of ignition threshold under all exposure geometries.

Fifth, gas concentration measurements represent integrated exhaust values under the ventilation conditions of the NFPA 286 enclosure. They do not replicate occupant breathing-zone stratification, transient door-opening effects, or crowd-induced airflow disturbances that may occur in real assembly occupancies. Accordingly, tenability implications must be interpreted in relation to measured trends rather than as direct predictions of occupant exposure time in the historical incident.

Sixth, although evacuation dynamics and human behavior in the Kiss nightclub have been examined in a separate computational study conducted by the same research group, those analyses are not integrated into the present article. The current manuscript is intentionally restricted to material combustion behavior and enclosure response under NFPA 286 conditions. Therefore, while thermal exposure and gas concentration results are discussed in relation to established tenability criteria, no direct coupling with evacuation modeling or performance-based life safety simulation is undertaken within this study. The interaction between material fire growth and occupant movement dynamics remains an important complementary dimension, but it lies beyond the defined analytical scope of the present investigation.

An additional limitation concerns hydrogen cyanide (HCN) formation. Forensic reports from the original criminal investigation[1] identified the presence of nitrogen-containing decomposition products consistent with flexible polyurethane combustion, including HCN. However, quantitative measurement of HCN generation was not performed in the present experimental program. The absence of controlled analytical testing for HCN represents a relevant constraint, as this gas is a well-documented toxicant in polyurethane fires and may significantly influence tenability under enclosure conditions. Consequently, while carbon monoxide and oxygen depletion were quantified, the toxicological assessment presented here does not capture the full spectrum of combustion gases potentially generated by the original material. Future investigations incorporating targeted HCN quantification under compartment-scale conditions would provide a more comprehensive evaluation of toxic hazard.

Finally, regulatory interpretation is limited to the performance criteria referenced within NFPA 286 Annex C.2 and to established tenability guidance. The study does not propose immediate modification of any specific code provision, nor does it claim that one test method alone is sufficient to characterize all fire risk scenarios. Rather, it provides experimental evidence relevant to enclosure fire development under a defined installation and ignition context.

Within these boundaries, the findings remain robust. The experimental program reproduced key physical mechanisms associated with untreated flexible polyurethane ceiling linings under localized ignition, including rapid heat release escalation, early smoke production, oxygen depletion, and flaming melt-dripping. The limitations described above define the scope of applicability of the conclusions and clarify that the results should be interpreted as scenario-specific rather than universally generalizable to all polyurethane foam applications.

4. Conclusions

4.1 Compartment Fire Severity and Material Adequacy

The experimental evidence obtained under NFPA 286 compartment conditions demonstrates that the untreated flexible polyurethane foam evaluated in this study exhibits combustion characteristics consistent with rapid ceiling flame spread. The measured peak heat release rate of 2465 kW substantially exceeds the 800 kW criterion referenced in Annex C.2 of NFPA 286, indicating noncompliance with the heat release performance threshold commonly used for interior finish evaluation.

Although the total smoke released (258 m²) remained below the 1000 m² criterion, this compliance does not offset the significance of the thermal findings. The fire growth was characterized by rapid escalation to peak intensity within approximately three minutes, concentrated early energy discharge (total heat release ≈142 MJ), and temporal alignment between peak heat release, oxygen depletion, and maximum carbon monoxide formation. These coupled behaviors indicate that thermal severity governed the enclosure response.

Full-scale measurements further documented upper-layer temperatures approaching 800°C, combined convective and radiative heat flux exceeding 20–25 kW/m², and the occurrence of flaming melt-dripping. When interpreted against established tenability references, these exposure levels lie within injury-producing regimes and are incompatible with prolonged occupant survival in densely occupied assembly environments.

Taken together, the enclosure-scale heat release magnitude, rapid fire growth, gas-phase effects, and secondary flaming phenomena indicate that the tested foam is unsuitable for use as an exposed interior lining in high-occupancy assembly occupancies. The conclusion is confined to the configuration and conditions evaluated in this study.

4.2 Implications for Performance-Based Evaluation

The results reinforce the governing role of heat release rate in enclosure fire severity. The temporal coupling observed between peak heat release, oxygen consumption, carbon monoxide production, and smoke development confirms that multiple tenability threats derive from combustion intensity. Heat release rate functions as the primary driver of upper-layer temperature rise, radiative feedback, and gas-phase composition, thereby shaping the evolution of enclosure conditions.

At the same time, the divergence between compliance in total smoke release and failure in peak heat release underscores the limitations of single-criterion or binary evaluation frameworks. Fire performance parameters exist on continuous scales, and their safety significance depends on occupancy context, installation geometry, and human vulnerability. In high-occupancy assembly settings, rapid thermal escalation may be decisive even when other criteria are satisfied.

The NFPA 286 Room Corner Test provides a robust method for assessing interior finish contribution under defined compartment conditions, integrating material combustion, ventilation, and enclosure feedback. However, as with any standardized configuration, the findings are bounded by the prescribed geometry, ignition protocol, and ventilation characteristics. The study did not include additional small-scale reaction-to-fire tests or replicate full-scale testing across all foam formulations, and conclusions should therefore be interpreted within the limits of the experimental program.

Within those limits, the present data provide quantitative evidence linking intrinsic material combustion behavior to enclosure-scale thermal severity. For performance-based fire safety evaluation in assembly occupancies, interpretation of material suitability should prioritize heat release characteristics in conjunction with smoke production, gas evolution, and secondary mechanisms, rather than reliance on isolated threshold compliance.

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