Best Practice

Facility: Nevada National Security Site (NNSS) Nuclear and Non-Nuclear High Hazard Facilities

Best Practice Title: Combustible Loading Limit Restricts Fire Size to the SSC Capability within the Fire Protection Area

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Brief Description of Best Practice: Best practices were observed for the use of an administrative control that limits the amount of combustible loading for an applicable fire area. The Combustible Loading Limit (CLL) restricts fire growth to an amount that will cause the fire to be fuel and oxygen limited and suppressed/controlled and to remain within its fire area.

Why the best practice was used: The NNSS nuclear, radiological, and non-nuclear high hazard facilities achieved significant successes in the areas of managing combustible materials. Limiting the amount of combustible materials contributes to limiting the fire size within a given area, precluding the potential to overwhelm the ability of the automatic fire suppression system (FSS). The systems employed and the approaches used, as well as the lessons learned, are best practices suitable for U.S. Department of Energy (DOE) Complex-wide application.

What are the benefits of the best practice: The Energy Facility Contractors Group (EFCOG) Nuclear and Facility Safety Subgroup believes that the recommendations establish a quantitative basis for determining an acceptable CLL in relation to structure, system, and component (SSC) capabilities. The NNSS Management and Operations (M&O) contractor, National Security Technologies, LLC, recognizes that the CLL enables more mission activities and facility usage while providing a conservative and quantitiative basis for the CLL.

What problems/issues were associated with the best practice: Acceptance of the control was expressed by some, but not all personnel. Restricting the use of wood pallets (and the use of metal pallets as an alternative) met with resistance from personnel who were accustomed to procuring bulk items shipped for arrival at a facility on wood pallets. The Best Practice CLL could be applied to facilities that have an automatic FSS, but may not be appropriate for facilities that do not have an automatic FSS. Evaluations by local Fire Protection and Building Structure Engineers, among other appropriate disciplines, regarding criteria such as facility design, fire area determination, and mission/operational needs are important prior to establishing any CLL applied to a specific facility.

How the success of the Best Practice was measured: The CLL is used at NNSS nuclear and non-nuclear high hazard facilities that have an automatic FSS and have been evaluated for suitability.

Description of process experience using the Best Practice: The NNSS nuclear facilities achieved significant successes in the areas of establishing a quantitative basis for limiting fixed and transient flammable and combustible materials to an amount that will not overwhelm the capabilities of the available SSCs to prevent and or mitigate a fire in a relevant scenarios.

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1.0 INTRODUCTION

The remarkable volume of available literature regarding the science and physics of fire, combustion, and firefighting reveals more than 100 years of recorded thought-provoking topics relevant to this paper. These topics include but are not limited to the following:

1. Correlation between fuel load and fire duration
2. Standard time-temperature curve from ASTM E119 (2015)
3. Compartmentalization
4. Fire suppression and its effects on control, intervention, oxygen depletion, decay, and extinguishment
5. Effect of ventilation (critical role of ventilation) and fenestration on available oxygen
6. Characteristics of fuel (geometry, density, flammability, and height) and relation to fire growth, severity, and duration
7. Fuel pools (flammable versus combustible) and their effect on fire growth rate upon ignition
8. Fuel (fire) load density represents the quantity of combustibles expected to be present in the fire area and is a reasonable basis for design-level fires

This paper focuses on combustible loading as a Specific Administrative Control (SAC) and what the SAC accomplishes. The above topics were considered in developing the essential elements of the SAC and determining how to design the control to achieve maximum effectiveness while keeping the control relatively easy to implement and maintain. The purpose of this control is to limit the combustible and flammable materials in a fire area to such an extent that the fire does not exceed the capacity of the fire area SSCs; therefore, the fire does not propagate outside the fire area and the fire is extinguished. Depending on the facility construction and the suitability evaluation of this control, an alternative purpose may limit the combustible materials in a fire area to minimize the potential for fire spread, duration, and impact on facility SSCs and various materials at risk.

The basic method for controlling building fires is through the use of water, which is typical. Another consideration for limiting fire propagation is by compartmentalization in order to confine/constrain the fire to a specific fire area in a facility. Most nuclear and non-nuclear high hazard facilities may have implemented an administrative control that limits the fixed and transient flammable and combustible materials inside a building fire area to an amount that the facility FSS can control. Some remote facilities and some highly secure facilities may have more than 15-minute (min) response periods between the time of incipient fire and the arrival of fire department personnel.

The use of an administrative control that limits combustible and flammable materials will limit fire size, growth rate, and duration. Fires areas are bounded by construction that has a fire rating, including fire doors that are required to remain closed. If an area is not bounded by fire-rated construction, then it cannot be considered a fire area. If the fire area can be kept closed, such that it does not self-ventilate or become ventilated by building occupants or by the fire department, then available oxygen would also be held back. This paper focuses on unintended fires involving combustible and flammable materials inside a building fire area.

2.0 FIRE PROTECTION PROGRAM AND COMBUSTIBLE LOADING SPECIFIC ADMINISTRATIVE CONTROL

2.1 Elements of Fire Protection Program

DOE nuclear, radiological, and non-nuclear high hazard facilities are managed with regulatory and contractual requirements, which implement the NNSS M&O contractor's safety management programs (SMPs), including Fire Protection, among others. A Fire Protection Program consistent with DOE-STD-1066-2012 contains the following elements:

- For Hazard Category 1, 2, or 3 nuclear facilities, structural materials shall be noncombustible
- Transformers installed inside buildings shall be of a dry type, with no combustible dielectric fluids
- Fire Risk Assessment
    - Fire Protection Assessment (FPA)
    - Fire Hazards Analysis (FHA)
    - Flammable and Combustible Material Loading Evaluation and Limits
- FSS (include Equivalencies or Exemptions)
    - Fixed Wet Pipe and/or Extinguishers (NFPA 13/NFPA 10)
- Fire Detection and Alarm System (NFPA 72)
- Fire Areas and Fire Barriers (NFPA 221/NFPA 80)
- National Electrical Code (NFPA 70)

2.2 Nuclear, Radiological, and Non-Nuclear High Hazard Facility Combustible Loading

A Fire Protection Program (FPP) is required by 10 CFR 851, "Worker Safety and Health Program," and DOE O 420.1C, "Facility Safety." An FPP includes the following criteria:

- A comprehensive CLL based on national standards should be implemented.
- The CLL should be correlated with fire area SSC capabilities.
- Storage racks for special nuclear materials shall be of noncombustible construction.
- The structure's fire resistance rating shall be designed for the maximum fire exposure and the duration anticipated, but not less than 2 hours (hr).

2.3 Evolution of Combustible Loading Limit

The CLL at the NNSS nuclear and non-nuclear high hazard facilities has evolved over the last 15 years. The initial administrative control was that "no wood pallets" would be used to stage or store hazardous materials. Fixed combustibles was initially evaluated and managed through Configuration Management and/or work control. With knowledge and experience, the following criteria were combined:

- Wood pallets would be removed from the building/facility as soon as practical.
- Metal scaffolding would be used in place of wood and plastic (combustibles).

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- Wood, cardboard, and transient combustible materials should be minimized.
- Docks/Portals and Exit/Egress pathways should be kept clear.
- Combustibles such as plastics and flammable liquids should be addressed.
- A specified CLL should be considered when applicable:
  - Specify the bounding area (operations area, storage area, or entire fire area designated by fire-rated construction).
  - Determine when the control applies (e.g., when radioactive materials, explosive, or other hazardous materials are present, but not during maintenance activities when hazardous materials are not present).

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A. Transient combustibles/flammables in the presence of radioactive materials or exposed high explosives shall be controlled.

B. Combustibility will be low.

- Combustibility of building contents that are considered low are classified as a Class I–IV commodity per National Fire Protection Association NFPA 13, *Standard for the Installation of Sprinkler Systems*.

C. The quantity will be moderate—no more than 200,000 Btu/ft^2 [British thermal units per square foot].

- As discussed in the 20th Edition of *The SFPE Fire Protection Handbook of Fire Protection Engineering*, Chapter 1, “Confinement of Fire in Buildings,” “British Fire Loading Studies” section, Page 18-7.

D. Stockpiles of combustibles will not exceed 8 feet (ft) high.

- NFPA 13 uses the terms “combustibles” and “contents” interchangeably when discussing storage heights. This requirement is to be applied to all materials stored within the respective building or specified area.

E. Fires will have moderate rates of heat release.

F. The combustibles/contents in the facility are bounded by Class I–IV commodities that are considered as having moderate rates of heat release and therefore will produce fires with moderate rates of heat release.

Consider a Limiting Condition for Operation (LCO) formatted SAC, such that Mode Applicability, Process Area Applicability, as well as Conditions, Actions, and Completion Times are established to maintain the transient combustibles/flammables within the analyzed CLL. Appendix A of this paper provides an example calculation.

An SAC appropriate for 2-hr automatic fire suppression capability (see DOE-STD-1066-2012, Appendix A) can be used for a fire area where the SSCs are designed to survive a 2-hr fire that does not exceed the above heat release rate (HRR) from combustion products.

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The NNSS M&O contractor's FPP regarding the Control of Combustibles states the following:

1. Limit combustibles and ignition sources to those materials and quantities necessary to support work activities.
2. Use metal planking, where practical, in the construction of scaffolding.
3. **IF** metal planking is not practical, **THEN** use pressure-treated, fire-retardant coated lumber.
4. Use metal or noncombustible pallets where practical.
5. Ensure that plastic or fabric tarpaulin sheets are Underwriters Laboratories (UL) listed fire-retardant materials unless waived by the Fire Marshal or Fire Protection Engineer (FPE) Authority Having Jurisdiction (AHJ).
6. Maintain a 30-ft firebreak around the perimeter of buildings and along substation fences.
7. Do not allow empty combustible shipping containers and pallets to accumulate.
8. Maintain a 50-ft radius firebreak around explosives magazines and magazettes.
9. Ensure that hazardous materials are shipped to the NNSS on pallets compatible with the materials being shipped. The use of wooden pallets to ship hazardous materials should be minimized. The Chemical AHJ and/or MSDS [Material Safety Data Sheet] or SDS [Safety Data Sheet] should be consulted prior to ordering hazardous materials.
10. Ensure that combustibles are controlled in accordance with an approved procedure for Housekeeping and Fire Protection.

2.4 Noncombustible and Combustible Materials and Fire Suppression

Further considerations included the following criteria:

A. Noncombustible pallets (e.g., metals, plastics compliant with NFPA or IFC [International Fire Code] requirements, or materials approved by an FPE for this application) are required for transuranic container storage.

B. Portable fire extinguishers will be readily assessable and nearby.

C. All flammable and/or combustible materials (fixed and transient) must be minimized to the extent practicable.

The SAC described above is appropriate for a building or facility with no automatic fire suppression capability.

2.5 Fire Scenario Analysis

Fire phenomena are of interest in evaluating the effectiveness of the control set (e.g., the ability of fire-rated construction and sprinklers to mitigate the event). Other important effects of fire include environmental challenges to SSCs. Flame, heat, smoke, and intervention (e.g., water spray) all can have negative impacts on the systems relied upon for facility safety.

The facility's FHA serves as input to the nuclear facility DSA [Documented Safety Analysis] or non-nuclear high hazard facility Authorization Basis (AB) document fire scenarios. Additional analyses using NFPA and good engineering practices (e.g., Society of Fire Protection Engineer [SFPE] methods) serve the purpose of evaluating the impact on hazardous materials and SSCs.

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This section presents the summary information needed to understand and evaluate the progression and severity of fire events. The following subsections describe the phenomenology of fire propagation (i.e., ignition, growth, steady state or peak and decay). Analytical solutions presented herein are based on empirical correlations that have been shown to provide reasonable engineering predictions; references to publicly available methodology guides, manuals, standards, or codes are provided where applicable.

The analytical methods presented in this paper focus on simple fire phenomenon. Complex models involving multiple rooms and openings or the need to understand detailed heat transfer characteristics can be effectively modeled using computer-based analysis. The Consolidated Model of Fire and Smoke Transport (CFAST) is a Central Registry Toolbox Code approved for use in safety basis (SB) or AB development; a DOE technical report (DOE/EH-4.2.1.4) is available for further information (DOE 2004). CFAST is a two-zone model that breaks a room into a hot upper zone and a cold lower zone and assumes smoke stratifies in two layers. An example of CFAST fire modeling is provided in Section 6.0.

Let us consider fire progression and prevention. A fire must have three elements to start: (1) fuel, (2) oxygen, and (3) an ignition source. Sustaining a fire is a four-part process that is captured in the tetrahedron. NFPA states:

> The most elementary view of flammability is provided by the fire triangle, which indicates that three components, fuel, oxidizing agent, and heat, are necessary to start a fire. However, the fire triangle does not describe all the conditions for a flaming fire because it does not include the chemical chain reactions and reactive molecules in flame gases. A more complete visual image of flammability is therefore provided by the fire tetrahedron, which recognizes that in order for flames to exist and not be extinguished, uninhibited chain reactions are necessary in addition to fuel (in a gaseous or vapor state), oxidizing agent, and heat.

The quantity and geometry of fuel (e.g., flammable/combustible materials) become a precursor to a fire event and affects its size, duration, and HRR. This is directly applicable to buildings that contain combustible and flammable materials. Since we cannot eliminate oxygen in a facility occupied by workers, consider limiting the amount of fuel or flammable/combustible materials and their configuration to restrict the size of a fire.

An SAC tied to national standards is a suitable means for limiting the amount of flammable/combustible materials in a facility fire area. The size and duration of the fire is proportional to the amount and configuration of flammable/combustible materials involved. By limiting the types and amount of flammable/combustible materials, and evaluating their configuration the fire size can be limited and the fire duration shortened. The fire event is design limited to within the capabilities of the FSS based on its classification and the fire duration is then limited to less than the rating of the fire barriers.

The control should be specific, measureable, verifiable, easily implemented, and sustained over a period of time. The control for combustible loading should clearly state when it is applicable. Other passive fire controls include providing materials that meet NFPA flame and smoke spread requirements for interior finishes, materials incorporating fire retardants, coating and wrapping, rated construction such as fire walls and barriers, and separation of combustible materials from ignition sources. Active controls are the application of agents to control, suppress, and/or extinguish.

Fire growth can be summarized into four distinct phases: ignition, growth, steady state or peak, and decay. Ignition can occur when flammable vapors are present in sufficient quantity to be ignited; this can occur because of the release of a flammable gas, spillage of a flammable liquid, or heating of a combustible liquid or solid material (pyrolysis). Following ignition of the initial fuel source, neighboring materials can be heated through direct flame impingement and/or heat transfer. The view factor or geometry factor plays a key role in heat transfer and the pre-heating of virgin fuels and can dramatically increase the overall growth rate of the fire.

Oxygen-limited fires occur in enclosures where sufficient openings are not available to support the burning of all combustibles in the enclosure. A fire can remain in its steady state until all the available combustibles are burned or when intervention takes place (fire department response, FSS, etc.). Intervention of the fire can result in direct extinguishment or control.

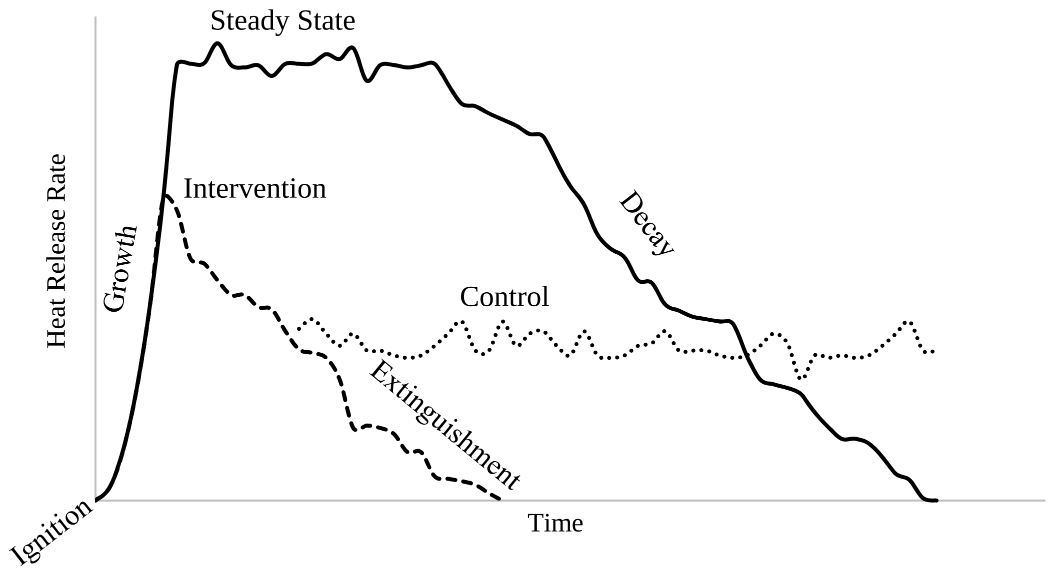

Figure 1. Fire Growth Model

3.0 EFFECTS AND CONSEQUENCES OF FIRE

Other important effects of a fire event include environmental challenges to SSCs. Heat, smoke, fire embers, automatic FSS actuation, and intervention (e.g., hose stream from fire department response) all can have negative impacts on other SSCs relied upon for facility safety.

The strength and stiffness of structural steel begins to decrease when heated, leading to possible deformation and failure. Structural, reinforced concrete also may begin to degrade when it is subjected to extreme temperatures. This effect is referred to as spalling. Consideration should be given to structural members located near postulated design basis fires. Building codes provide prescriptive fire ratings for structural members; however, detailed analytical methods can be used for the design of critical structural components and should include heat transfer analysis and consideration of steel properties at elevated temperatures (Buchanan 2002).

Radiant heating and direct flame impingement can cause the failure of both passive and active SSCs. The temperature limits of valves, motors, sensors, air filters, etc., should be considered in conjunction with radiant heating models when reviewing the impacts to SSCs from design basis fires.

4.0 PROTECTIVE FEATURES AND SYSTEMS

This subsection discusses the considerations that can be used to evaluate the capability of protective features and systems.

4.1 Automatic Fire Suppression System

There are two considerations with a typical automatic FSS:

1. Will the system recognize and respond to a fire signature or signal?
2. Will the system control or extinguish the fire?

The requirement to install an FSS depends on the occupancy classification of a facility and is driven by building codes. The types of FSSs that can be found in DOE facilities and their respective installation requirements are found in standards such as NFPA 13, NFPA 15, NFPA 750, NFPA 2001, etc. Actuation requirements for system components and the system as a whole are dependent upon the type of FSS.

FSS designs are based on a qualitative occupancy description found in NFPA 13. There are five occupancy-based design flow curves, and the appropriate occupancy curve is selected during the design process based on the expected use.

If the system is designed and installed consistent with NFPA 13 and maintained consistent with NFPA 25, an automatic sprinkler system is expected to control or suppress the fire, provided the building contents (i.e., combustible and flammable materials) are within the appropriate classification of commodities based on the occupancy classification. Traditionally, automatic fire sprinkler systems are designed using the "fire control" approach which means that the sprinkler heads are expected to operate around the surrounding fire area. The sprinklers directly over the fire area may not extinguish it (although they often do), but they work together to cool the atmosphere and prevent additional sprinklers from operating (NFPA Handbook).

The safety analysis, as part of the SB, relies on the FHA that provides the determination of the adequacy and effectiveness of the FSS based on the appropriate occupancy classification. Depending upon its adequacy and effectiveness, the automatic sprinkler system may perform a preventive or mitigative control for the mitigated accident analysis for an existing facility.

4.1.1 Fire Barriers

Firewalls, fire barriers, and spatial separations are often provided to achieve life safety and property protection goals. This section describes the standards and guides that can be used to evaluate compartmentation. The desired design function will affect the barrier selection. NFPA 221 (2006) has three distinct wall definitions. The key difference between the definitions is the expectation of structural stability during and following a fire. A fire barrier may be a fire-rated assembly that is designed and built to survive a specified duration (e.g., 1 hr or 2 hr) fire. The NFPA 221 definitions are as follows:

> **<u>Fire Barrier Wall. A wall, other than a fire wall, having a fire resistance rating. [NFPA 221: 3.3.14.5]</u>**
>
> Fire Wall. A wall separating buildings or subdividing a building to prevent the spread of fire and having a fire resistance rating and structural stability. [NFPA 221: 3.3.14.6]

The term "Fire Barrier" is a generic term that includes Fire Barrier Walls, Fire Walls, horizontal fire barriers (e.g., floors and ceilings), and sloped fire barriers (e.g., roofs) having a fire resistance rating. The term has a specific definition in the NFPA standards (NFPA 101, NFPA 801, NFPA 805, NFPA 5000, etc.).

FM Global (2000), FM Global (2007a), and FM Global (2007b) provide additional information that can be used in evaluating fire barriers where Highly Protected Risk is a consideration.

For most applications, the fire resistance is reported in terms of the ASTM E119 equivalent hourly rating. The hourly rating allows for qualitative evaluation of the stability and strength of the fire walls and construction associated with the structure, roof, and load bearing walls of the building under fire exposure.

As can be seen in Equation (2), the fire test curves used to define the hourly rating of fire barriers may not be representative of a design basis fire. Generally, fire barriers that meet applicable codes and standards can be assumed to survive and prevent propagation. However, for high challenge fires or fire barriers credited to prevent substantial consequences, the FHA or accident analysis should consider the barrier's performance against the given design basis fire. This is accomplished by the listing associated with construction materials.

5.0 CALCULATION METHODS FOR FIRE ANALYSIS

Correlations based on experiments and testing for numerous phenomena related to fire provide reasonable estimates for modeling and analysis. Several of these estimates can be applied as hand calculations. This subsection introduces some basic calculation methods commonly used for accident analysis. Extensive analysis techniques are documented and available in various NFPA standards and in *The SFPE Fire Protection Handbook of Fire Protection Engineering* (NFPA 2008). This section is provided to show the math behind the fire models and standards. However, if the reader would like to skip the math in Section 5, then skip to Section 6 for the results of the example fire modeling or Section 7 for the summary.

5.1 Heat Release Rate (HRR)

For most fire scenarios, the combustible loading and configuration are well established. It is usually necessary to understand the unmitigated fire potential in terms of HRR. The two examples in Sections 5.1.1 and 5.1.2 below provide detailed methods for determining the potential HRR for a fire involving liquids and solids, respectively. To determine the maximum potential HRR, the fires are assumed to be fuel-limited with adequate oxygen to support the full involvement of the fuel. Combustion efficiency can be represented by chi (X) and ranges from 0–1. This scenario would require chi (X) to be one, which represents 100 percent efficiency. Both extreme ends of the range (i.e., 0 or 1) are impractical. However, this assumption will produce higher mass-loss rates, and thus shorter durations.

5.1.1 Pool Fire Heat Release Rate

Liquid pool fires can occur following a release of flammable or combustible liquid. When a liquid is being stored under pressure above its normal boiling point, a small amount will flash into a vapor, with the remaining un-flashed liquid remaining to form a pool. The geometries of pool fires are dependent upon the surroundings.

Common scenarios include the following:

- A spill into a diked area or sump followed by ignition
- An unconstrained spill onto a hard surface
- An unconstrained spill onto a permeable surface (e.g., soil)
- A flowing spill that is ignited

Methods to establish the HRR for these scenarios are described in the *SFPE Handbook.* Contained or confined spills are covered in NFPA 2008, Section 1, Chapter 3, "Heat Release Rates." The other three scenarios are described in NFPA 2008, Section 2, Chapter 15, "Liquid Fuel Fires."

Typically, pool fires are assumed to be circular, but square and similar shapes can be estimated using an equivalent area circle. Highly elongated shapes are not applicable to the methods described.

Example: A 100-gal (0.38 m^3) kerosene spill, which is contained by a 3-meter (m) by 5-m diked area, is ignited. The objective is to estimate the HRR from the burning pool. Because the diked area is rectangular, an effective pool diameter is estimated:

$$D_{eff} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(3\,\mathrm{m})(5\,\mathrm{m})}{\pi}} = 4.4\ \mathrm{m} \tag{1}$$

Where:

D_{eff} = effective pool diameter (m)

A = pool fire area (m^2)

NOTE: These hand calculations (pool and pallet fires) do not include a burn rate adjustment to get from the typical pool or pallet fire HRR calculation, adjusting for the burn rate, and arriving at the HRR.

The HRR is estimated from:

$$\dot{q} = \Delta h_c \dot{m}''_{\infty} (1 - e^{-k\beta D}) \times A \tag{2}$$

Where:

$\dot{q}$ = HRR (MW)

Δh_c = net heat of combustion (MJ/kg)

$\dot{m}''_{\infty}$ = mass loss rate per unit area (kg m^{-2} s^{-1})

$k\beta$ = extinction absorption coefficient and beam length corrector (m^{-1})

D = Pool fire diameter (m)

For kerosene, Equation (2) becomes:

$$\dot{q} = (43.7\ \mathrm{MJ/kg})\left(0.039\frac{\mathrm{kg}}{\mathrm{m}^2\cdot\mathrm{s}}\right)\left(1 - e^{-(3.5\,\mathrm{m}^{-1})(4.4\,\mathrm{m})}\right)[(3\,\mathrm{m})(5\,\mathrm{m})] = 25.6\ \mathrm{MW} \tag{3}$$

For a uniform pool depth, the approximate burn duration for the fire is:

$$t = \frac{\rho V}{\dot{m}''_{\infty}(1 - e^{-k\beta D}) \times A} \tag{4}$$

Where:

t	= fire duration (seconds)
ρ	= liquid density (kg/m^3)
V	= spill volume (m^3)

For the postulated 100-gal spill, the fire duration from Equation (4) is:

$$t = \frac{\left(820 \frac{kg}{m^3}\right)\left(0.38\, m^3\right)}{\left(0.039 \frac{kg}{m^2 \cdot s}\right)\left[1 - e^{-\left(3.5 \frac{1}{m}\right)(4.4\ m)}\right]\left[(3\, m)(5\, m)\right]} = 533\, sec = 8.9\, min \tag{5}$$

5.1.2 Pallet Fire Heat Release Rate

Wooden pallets are common in many facilities and, depending on their configuration, can produce a high HRR. A correlation to estimate the HRR is in NFPA 2008, Section 1, Chapter 3, "Heat Release Rates." The energy release rate from a stack of wood pallets is:

$$\dot{q}'' = 919\left(1 + 2.14 h_p\right)\left(1 - 0.03M\right) \tag{6}$$

Where:

$\dot{q}''$	= HRR per unit area (kW/m^2)
h_p	= stack height (m)
M	= wood moisture content (percent)

This equation is valid for stacks that are higher than 0.5 m. Below this height, the equation over-predicts the burning rate. It is based on a heat of combustion value of 12,000 kJ/kg.

<u>Example</u>: For a 0.6-m high pallet stack with a nominal area of 1.2 m x 1.2 m (e.g., a five-pallet stack of typical 4-ft by 4-ft wooden drum pallets, 4.75 in. height from 5/8 in. top and bottom decking plus 3.5-in. forktine opening), and a typical 10% moisture content of the wood, based on Equation (6), the unit HRR is:

$$\dot{q}'' = 919\left[1 + 2.14(0.6\, m)\right]\left[1 - 0.03(10\%)\right] = 2{,}090 \frac{kW}{m^2} \tag{7}$$

The HRR would be:

$$\dot{q} = A\,\dot{q}'' = (1.2\text{ m})^2\left(2{,}090\,\frac{\text{kW}}{\text{m}^2}\right) = 3{,}010\text{ kW} = 3\,\text{MW} \tag{8}$$

5.1.3 Flame Height

Determination of a fire's flame height can be helpful in order to estimate the likelihood of further propagation or structural impacts. The flame height of a fire may be predicted using Equation (9) below. This represents the height of the flames above the base of the fire (NFPA 2008).

$$H = 0.23\dot{Q}^{2/5} - 1.02D \tag{9}$$

Where:

H = flame height (m)

$\dot{Q}$ = heat release rate (kW)

D = flame diameter (m)

Example: Equation (9) can be applied to fires reasonably approximated by a circle. For this example, the flame height for the pallet fire developed in Equation (9) will be found.

The effective area from Equation (1) is:

$$D_{eff} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(1.2\text{m})(1.2\text{m})}{\pi}} = 1.4\text{m} \tag{10}$$

The flame height from Equation (9) is:

$$H = 0.23(3{,}010\,\text{kW})^{2/5} - 1.02(1.4\,\text{m}) = 4.2\,\text{m} \tag{11}$$

5.1.4 Enclosure Fire Dynamics

Fires within an enclosure, such as a glovebox or a room in a building, exhibit a distinct behavior that differs from well-ventilated fires. There are two primary differences when considering an enclosure fire: (1) interaction with the enclosure boundary and (2) the development of an upper layer (the hot, gaseous products of the fire that collect in the compartment). In both cases, the boundary and the upper layer have the ability to reflect and radiate heat within the enclosure. Heat transfer effects out of the boundary also affect the behavior of the fire.

Flashover is a phenomenon of importance when analyzing enclosure fires. Flashover is "A transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space" (NFPA 921 [2011]). The occurrence of flashover is dependent upon several variables such as the available vent area, heat transfer from the enclosure boundary, and HRR of the fire; flashover occurs when the temperature of the enclosure, with consideration given to the radiative effects of the upper layer, is sufficient to ignite all of the combustibles in the enclosure. Upon transition to flashover, the fire is in a ventilation-limited state.

5.1.5 Flashover

Upper layer temperatures, such as those found using the methods discussed above, can be used to predict flashover. Upper layer temperatures of 500°C to 600°C are widely considered to be associated with the onset of flashover (NFPA 2008). More rigorous flashover predictions can be performed using the methods from NFPA 555.

A common screening criterion for predicting flashover in a compartment with a single vent opening is detailed in NFPA 555. This estimated HRR necessary to achieve flashover can be compared to the HRR for the design basis fire, as found using methods similar to those presented above.

5.1.6 Solid Fuel Ignition and Radiant Heating

Describing the progression of a design basis fire requires an analysis of potential propagation. Specifically, collocated combustible materials can be ignited by a fire; determining if these combustibles will ignite in a given fire or determining the minimum separation distance to prevent ignition can be useful.

There are two basic ignition metrics: heat flux and surface temperature. Both metrics may be used, but heat flux is the more common method to predict solid fuel ignition. A commonly accepted default ignition flux used for cellulosic materials is 12.5 kW/m^2. For additional ignition flux data, see the *Ignition Handbook* (Babrauskas 2003).

The methodology presented below estimates the heat flux imposed on a target.

NFPA 555 (2013) provides a methodology to estimate the heat flux imposed on a target:

$$\dot{q}'' = F_{f-t} E_f \tag{21}$$

Where:

$\dot{q}''$ = the heat flux at the target fuel package (kW/m^2)

$F_{f\text{-}t}$ = the view factor between the flames and a differential area on the target fuel package (unitless)

E_f = the emissive power of the flames (kW/m^2)

When using the flame height estimation in Equation (9), the corresponding emissive power correlation is (NFPA 555):

$$E_f = 58\left(10^{-0.00823D}\right) \tag{22}$$

Where:

E_f	= the emissive power of the fire (kW/m^2)
D	= the fire diameter (m)

Figure 2 shows the view factor for a differential planar element (dA_1) of an object at a specified distance (h) to a finite-length, right circular cylinder, where the normal to the element passes through one end of the cylinder and is perpendicular to the cylinder axis. The view factor (F) is calculated as follows (Siegel et al. 1981):

$$F = \frac{1}{\pi H}\tan^{-1}\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{L}{\pi}\left(\frac{(X-2H)}{H\sqrt{XY}}\right)\tan^{-1}\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right) - \frac{1}{H}\tan^{-1}\left(\sqrt{\frac{(H-1)}{(H+1)}}\right) \qquad (23)$$

Where:

F	= the view factor
h	= distance from the object to the centerline of the cylinder
l	= the height of the cylinder
r	= the radius of the cylinder
H	= the distance from the object to cylinder diameter ratio (h/r)
L	= the cylinder height to diameter ratio (l/r)
X	= $(1+H)^2+L^2$
Y	= $(1-H)^2+L^2$

Since the solution above is for a right cylinder with the differential area at the base of the cylinder (i.e., fire), in order to obtain the peak heat flux, which occurs at the mid-height of the cylinder, the actual view factor is twice the value calculated using Equation (23), if the cylinder height is taken as half the fire height.

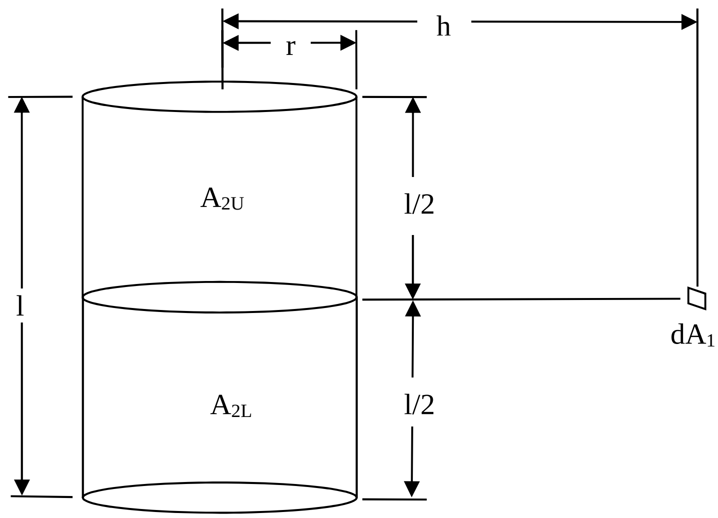

Figure 2. Adaptation of View Factor Geometry for a Fire Model

Example: For a 2-MW fire with a base diameter of 1.2 m, estimate the heat flux 0.5 m from the fire at the mid-height of the flames.

The emissive power from Equation (22) would be:

$$E_f = 58\left(10^{-0.00823D}\right) = 57\,\frac{kW}{m^2} \tag{24}$$

From Equation (9) the flame height would be:

$$H = 0.235(2{,}000kW)^{2/5} - 1.02(1.2m) = 3.69m \tag{25}$$

The view factor for a fire to object separation of 0.5 m is presented below:

$l = 3.69/2 = 1.845$ m

$r = 1.2/2 = 0.6$ m

$h = 0.5 + 0.6 = 1.1$ m

$H = h/r = 1.1/0.6 = 1.833$

$L = l/r = 1.845/0.6 = 3.075$

$X = (1+H)^2 + L^2 = (1+1.833)^2 + (3.075)^2 = 17.48$

$Y = (1-H)^2 + L^2 = (1-1.833)^2 + (3.075)^2 = 10.15$

$$F = \frac{\tan^{-1}\left(\frac{3.075}{\sqrt{(1.833)^2 - 1}}\right)}{\pi(1.833)} + \frac{3.075}{\pi}\left(\frac{((17.48) - 2(1.833))}{(1.833)\sqrt{17.48(10.15)}}\right)\tan^{-1}\left(\sqrt{\frac{(17.48)((1.833)-1)}{(10.15)((1.833)+1)}}\right) - \frac{\tan^{-1}\left(\sqrt{\frac{((1.833)-1)}{((1.833)+1)}}\right)}{1.833}$$

$$= 0.26$$

As discussed previously, this view factor is for a half-cylinder. The effective view factor is thus twice this value (0.52). The heat flux would thus be:

$$\dot{q}'' = (0.52)\left(57\frac{kW}{m^2}\right) = 30\frac{kW}{m^2} \tag{26}$$

6.0 RESULTS OF FIRE MODELING

CFAST fire modeling results are described in this section relevant to buildings constructed of noncombustible and fire-resistive materials (e.g., steel reinforced concrete walls, ceiling, and floor, steel doors and penetrations).

The first constrained model considered a round room with no open vents or doors, but with normal penetrations. Workers enter the room through a large opening after proceeding through a series of interlocked doors. A fire is postulated to start with an alcohol pool that ignites the floor cushioning material or other combustible material in the room. By constraining the model to the oxygen available in the room, the results show that the fire grew until it became oxygen limited at 650 sec (~11 min) after the fire started. At this time, the fire growth stopped at a maximum HRR of 5.6 MW. A short time later, the maximum upper layer room temperature was approximately 390°C.

The second constrained round room model considered the addition of two vents, one near the ceiling and the other near the floor to facilitate convective gas flow. The addition of these vents allowed fresh air to enter the room and allowed the hot combustion gases to escape. The modeling results showed that allowing for the oxygen replenishment had extended the fire’s duration. Nevertheless, the fire again became oxygen limited at 1,010 sec (~17 min); at this time, the fire growth stopped at a maximum HRR of approximately 4.3 MW. The maximum upper layer room temperature was approximately 358°C.

The third constrained round room model considered the effect of an open personnel access door. The two vents used in the previous model were also present in this model. The fire was able to burn for 1,530 sec (~26 min) before becoming oxygen limited. At that time, the fire growth stopped at a maximum HRR of 9.3 MW. However, the fire continued to burn and the upper layer room temperature continued to rise. The room reached flashover approximately 43 min after the fire started.

The combustible loading described above is far more than the quantity of common combustible equivalent materials consumed by any of the fire models described above. These models are considered conservative because some of the material that comprises the combustible loading is difficult to ignite and/or sustain combustion (e.g., floor cushioning materials and acoustic tiling). These models assume that all of the combustible materials in the room are available for consumption and are burned to completion.

Best Practice

The CFAST models above do not consider operation of the FSS. With the operation of the FSS, the fire duration and HRR is far less.

Consider the first two models with the doors shut; the fire duration is less than 15 min and the fire does not flashover (even without the FSS activating). In the first two cases, the SSCs involved (the building structure of walls, floor, and ceiling and the fire-rated door) survive the fire duration and HRR. For example, the fire duration (< 120 min) did not exceed the 2-hr rating for the walls, ceiling, and door.

Consider the third model with the open personnel access door; with the operation of the FSS, the fire is suppressed and the fire does not flashover.

7.0 SUMMARY

Placing controls on the fixed and transient combustible and flammable load limits directly impacts the fire size, growth rate, HRR, and duration. If the fixed and transient combustible materials are limited, and compliant with the commodity classification associated with the occupancy hazard, then the postulated fire should not exceed the SSC capabilities. Utilizing the classification and capability of the SSC (e.g., FSS) as the basis for determining the CLL will allow for increased facility usage and provide a quantitative basis for establishing the CLL.

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10.0 DISCLAIMER

DOE/NV/25946--2883

APPENDIX A
EXAMPLE FIXED AND TRANSIENT COMBUSTIBLE LOADING CALCULATION

Building: ________

Fixed Combustibles:

	Quantity	Total Btu
Ceiling/Acoustic Panels:	2,829 lb @ 7,696 Btu/lb	21,771,984
Exposed Electrical Cables:	0 lb @ 7,718 Btu/lb	0
Flammable Liquids:	0	0
PVC [Polyvinyl Chloride] Flooring:	1,200.0 lb @ 13,324 Btu/lb	15,988,800
Miscellaneous:	0	0

Total Fixed Combustibles: 37,760,784 Btu

Transient Combustibles:

Category	Item Description	Quantity	Btu/Unit	Total Btu
Paper	Kimwipes	100 lb	7,696/lb	769,600
	Tyvek	200 lb	7,696/lb	1,539,200
	Binders/Manuals	100 lb	7,696/lb	769,600
	Trash	20 lb	7,696/lb	153,920
Cotton	Gloves (cotton)	50 lb	8,771/lb	438,550
	Booties (cotton)	50 lb	8,771/lb	438,550
	Clothes	75 lb	8,771/lb	657,825
Plastic	Plastic Bags	200 lb	13,324/lb	2,664,800
	“Fantastik” cleaner	20 lb	13,324/lb	266,480
	Brattice Cloth	200 lb	13,324/lb	2,664,800
	Duct Tape	75 lb	13,324/lb	999,300
	Stanchions	30 lb	13,324/lb	399,720
	Cones	20 lb	13,324/lb	266,480
	Gloves (plastic)	10 lb	13,324/lb	133,240
	Booties (plastic)	5 lb	13,324/lb	66,620
	Equipment	350 lb	13,324/lb	4,663,400
	Expanded Polystyrene Foam Blocks	25 lb	18,000/lb	450,000

APPENDIX A (CONTINUED)
EXAMPLE FIXED AND TRANSIENT COMBUSTIBLE LOADING CALCULATION

Category	Item Description	Quantity	Btu/Unit	Total Btu
Oil	Hydraulic Oil	0 gal	157,794/gal	0
Rubber	Tires	20 lb	14,500/lb	290,000
Lubricants	Grease	0 gal	159,766/gal	0
Miscellaneous	Plastic* (chairs, etc.)	400 lb	13,324/lb	5,329,600
Total Transient Combustible Loading (Btu):				**22,961,685**

*Plastic Btu/Unit bounds other common combustibles such as paper, cotton, PVC, and wood.

Total Fixed and Transient Combustible Loading: 60,722,469 Btu

Total Fixed and Transient Combustible Loading
per Building Area of **1,769** ft^2 **34,326.0** Btu/ft^2

Occupancy Fire Load Classifications

Description	Occupancies of Moderate Fire Load
Average Fire Load of Net Floor Area	100,001–200,000 Btu/ft^2 (SFPE Fire Protection Handbook, **20th Edition**)
Building **1,769** (ft^2)	Transient Combustibles: **22,961,685 Btu** Fixed Combustibles: **37,760,784 Btu** Average: Btu/ft^2 = **34,326.0 Btu/ft^2** Combustible Loading at 8,000 Btu/lb: **4.290 lb/ft^2**
Average Fire Load in Limited Isolated Areas	400,000 Btu/ft^2

Storage less than 8'-0" high max: ☒ Yes ☐ No If No, record height: ___________

Acceptance Criteria Met? ☒ Yes ☐ No

Approvals:

Preparer (Print/Sign/Date)	**Approver (Print/Sign/Date)**

APPENDIX A (CONTINUED)
EXAMPLE FIXED AND TRANSIENT COMBUSTIBLE LOADING CALCULATION

Instructions for Completing the Combustible Loading Calculation

1. **Building:** Enter the building number.

2. **Fixed Combustibles:** For each specified fixed combustible, enter the quantities and convert these quantities to Total Btu by multiplying the quantity of fixed combustibles by the Btu/Unit values. Sum the Total Btu for the specified fixed combustibles and record the Total Fixed Combustibles (Btu value) for the building.

3. **Transient Combustibles:** For each item that comprises the building baseline transient combustible loading inventory, record the quantity value as appropriate and convert the quantity to the item-specific Btu value by multiplying the quantity of transient combustibles by the given Btu/Unit values. For items that are undefined in the Combustible Loading Calculation form, obtain a Btu/Unit conversion from the Fire Protection Engineer (FPE) and record the Total Transient Combustible Loading (Btu value) with an annotation of the NFPA or Standard reference. Sum all of the item-specific Total Btu values and record the Total Transient Combustible Loading Btu value.

4. **Total Fixed and Transient Combustible Loading:** Sum the Total Fixed Combustibles Btu value and the Total Transient Combustible Loading Btu value and record as the Total Fixed and Transient Combustible Loading Btu value.

5. **Total Fixed and Transient Combustible Loading per Building Area:** Divide the Total Fixed and Transient Combustible Loading Btu value by the applicable building area square footage, and record the Total Fixed and Transient Combustible Loading per Building Area in units of Btu/ft^2.

6. **Occupancy Fire Load Classifications:** Record the building square footage in the Description column in the table. Next, record the Transient Combustibles Btu, Fixed Combustibles Btu, and Average Btu/ft^2 in the Occupancies of Moderate Fire Load column. Next, compare the Average Btu/ft^2 with the maximum value of 200,000 Btu/ft^2 and determine if the Average Btu/ft^2 is below this value.

7. **Storage less than 8’-0” high max:** Check “Yes” if less than 8 ft. Otherwise, check “No” and record height.

8. **Acceptance Criteria Met?** Check “Yes” if the Average Fixed and Transient Combustible Loading per Building Area is less than or equal to the maximum value of 200,000 Btu/ft^2 as noted in Item 6 above. Otherwise, check “No” and contact the Facility Nuclear Operations Manager and the FPE immediately.

9. **Approvals:** The Preparer signs and dates the Combustible Loading Calculation form after validation of the Average Fixed and Transient Combustible Loading and forwards the form to the Approver, who signs and dates the form in support of the facility’s Building Status Board.