DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Washington, DC 20004-2901

November 9, 2017

The Honorable Frank G. Klotz
Administrator
National Nuclear Security Administration
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dear Administrator Klotz:

We completed a review of the adequacy of the Los Alamos National Laboratory Transuranic Waste Facility's safety basis. We note that the facility has begun limited operations and that the scope of operations will expand after the safety basis is revised in the spring of 2018. The current facility Safety Evaluation Report places defensible restrictions on the facility's near-term operations. Therefore, we conclude that the current TWF safety basis provides for adequate protection of public health and safety.

The enclosed report contains additional details and is provided for your information.

Yours truly,

Sean Sullivan
Chairman

Enclosure

c: Mr. Joe Olencz

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Report

September 25, 2017

MEMORANDUM FOR: S. A. Stokes, Technical Director

COPIES: Board Members

FROM: P. Foster, B. Caleca, M. Wright

SUBJECT: Transuranic Waste Facility Documented Safety Analysis Development Review

Facility Description. The Transuranic Waste Facility (TWF) is a new construction Hazard Category 2 nuclear facility designed to be Los Alamos National Laboratory's (LANL) new facility for storage, characterization, and intra-site shipping of newly generated transuranic (TRU) waste. Its mission is to temporarily store and characterize TRU and TRU mixed waste in preparation for shipment to the Waste Isolation Pilot Plant (WIPP). Operations allowed in the facility include filter replacements and container over-packing, but do not include the opening of waste containers. In total, TWF will be able to store and stage up to 1,240 drums or drum equivalents. Figure 1 is included to show the completed facility, which is divided between a general operational area and the Resource Conservation and Recovery Act permitted area where TRU waste operations can be performed. For reference, TWF is located at the intersection of Pajarito and Puye roads in Technical Area 63.

Figure 1 – Completed Transuranic Waste Facility

Review Background. Members of the Defense Nuclear Facilities Safety Board's (Board) technical staff have been following the development of the TWF safety basis throughout the design and construction of the facility. The Board's staff team reviewing this phase of the project primarily consisted of M. Bradisse, B. Caleca, P. Foster, A. Martin, and M. Wright. This report documents the team's assessment of the final TWF safety basis, approved in December 2016. The scope of this review did not include the safety basis implementation or the facility's transition to operations.

As part of its review, the Board's staff team held a teleconference on October 24, 2016, with personnel from Los Alamos National Security, LLC (LANS), and the National Nuclear Security Administration's (NNSA) Los Alamos Field Office (NA-LA) regarding development of the TWF documented safety analysis (DSA) and technical safety requirements (TSRs). Discussions centered on the latest revision of the draft DSA [1] and TSRs [2] that LANS submitted to NNSA in September 2016.

In addition to this formal interaction, the Board's staff observed comment resolution meetings between LANS and NA-LA personnel and the deliberations of the Senior Review Board (SRB) regarding the project safety evaluation report (SER). The SRB, comprised of senior NA-LA and NNSA personnel, was formed as part of an internal improvement action to better resolve differing technical opinions in safety analysis.

In November 2016, the TWF SRB held two meetings to assess the draft SER and to review dissenting opinions presented by NA-LA safety basis review team (SBRT) members. As a result of those meetings, the SRB concurred with two directed changes and two conditions of approval (COA) to the TWF DSA. The most significant of these include a temporary reduction in the facility material-at-risk (MAR) limit, prohibition of pipe overpack containers (POCs) in the facility, and restoration of the fire suppression system (FSS) to safety significant. POCs will be prohibited at TWF until the DSA has been updated to adequately capture the hazards associated with their storage. This uncertainty with POC hazards is a complex-wide concern and is being pursued by a Department of Energy (DOE) integrated project team. The facility MAR limit was lowered temporarily to reduce the consequence of any potential fire accidents until the FSS can be restored as a safety significant control. COA 1 requires LANS to submit updates to the DSA and TSR. The final SER approved by the SRB anticipates that the DSA will be updated within six months of the start of nuclear operations at TWF, and that the safety significant FSS will be fully implemented three months after the DSA update. The SRB concluded that this compromise provides adequate protection to the public while allowing ongoing nuclear operations to proceed as scheduled. It should be noted, however, that four out of the eleven members of the SBRT (as well as their direct supervisor) did not concur on the final SER approved by the SRB.

Following approval of the SER [3] in December 2016, the Board's staff team completed its review of the final TWF DSA [4] and TSR [5]. The team did not identify any new safety items with the documentation or the final control set and believes the safety basis is adequate to support operations as described in the SER. In addition to this document review, the staff team performed independent engineering calculations to assess the adequacy of two specific aspects of the safety analysis and controls.

Appendix A includes a table summarizing the safety items that have been closed as well as those that remain to be addressed in the planned DSA update. The open safety items are discussed in further detail in the following sections of this report.

Previously Identified Safety Items. The Board originally communicated five safety issues with the project in its Critical Decision (CD) 3 project letter [6] related to the TWF preliminary DSA [7]. In July 2017, the Board approved Policy Statement-6, *Policy Statement on Oversight of Design and Construction of Defense Nuclear Facilities*.[1] This Policy Statement defines new terms for nuclear safety deficiencies identified during reviews of design and construction projects. These terms include:

- *Safety Item*—any type of nuclear safety deficiency (i.e., Safety Observation, Safety Issue, or Issue of Adequate Protection).
- *Safety Observation*—a safety item that will not challenge adequate protection of public health and safety when the facility begins radiological operations. The Board may choose to communicate formally on these topics to provide independent advice and analysis to DOE.
- *Safety Issue*—a safety item for which the Board requires additional information to assess whether it could challenge adequate protection of public health and safety when the facility begins radiological operations.
- *Issue of Adequate Protection*—a safety item where the Board recommends corrective actions to ensure adequate protection of public health and safety when the facility begins radiological operations.

As documented in Appendix A, the Board's staff team found that three of the previous open Board Safety Issues would no longer be considered safety items. These are identified in the report as "closed" items. While there are still several minor concerns related to the documentation and implementation of the selected control sets, the staff team concludes that the controls meet the requirements laid out in DOE standards. The remaining open safety items are documented in detail following the summary of the closed safety items.

Sealed Sources Pressurized Release (Status: Closed)—Previous versions of the TWF DSA did not adequately document the hazards associated with sealed sources in fires and subsequently did not derive sufficient controls to prevent source pressurization and release. However, the current TWF control set includes credited fire-rated safes for the storage of sealed sources and an administrative fire-watch to reduce the likelihood of fires while the sources are in use. The Board's staff team concludes that this suite of controls is adequate to control the fire-related hazards associated with sealed sources.

Site Specific Deposition Velocity (Status: Closed)—At the time of the CD-3 project letter, the LANL-specific dispersion analysis was incomplete. The Board's staff team has since reviewed the completed analysis and agrees that the deposition velocity of 0.4 centimeters per second (cm/s) is appropriate for TWF.

[1] The policy statement can be found at: https://www.dnfsb.gov/content/ps-6-policy-statement-oversight-design-and-construction-defense-nuclear-facilities

Safety Classification of Non-combustible Roofs (Status: Closed)—In the project's preliminary DSA [7], the roofs of the waste storage buildings were improperly classified as safety significant. Since then, DOE has updated both the DSA and the applicable design documentation to capture the classification of the non-combustible roofs as safety class. The Board's staff team agrees that this classification is appropriate to prevent a potential common-cause failure and to maintain the credited fire separation distances between buildings.

Facility Worker Safety Analysis (Status: Safety Observation)—In its CD-3 project letter on TWF, the Board identified two hazard scenarios that underestimated the consequences to facility workers, which resulted in a set of safety-related controls that may not have been sufficient to protect facility workers. The specific examples used to illustrate this deficiency were: (1) a forklift tine puncture spilling the contents of a POC containing 1,800 plutonium equivalent (PE)-Curies (PE-Ci) of dispersible powder, and (2) a radiolysis-driven deflagration in the headspace of a drum discovered to be damaged or otherwise not compliant with the WIPP waste acceptance criteria. Without a thorough and clearly documented basis for facility worker hazards and controls, the Board noted that TWF may be missing required safety-related controls for worker safety.

- Forklift Tine Puncture: The project's position is that the facility worker will be able to evacuate upon the puncture of a POC, therefore minimizing the dose received by facility personnel. The Board's staff team does not believe that LANS has adequately justified this qualitative assessment (especially given the quantity of MAR associated with the accident). In order to quantify the associated risk, the staff team performed an engineering calculation to characterize the potential speed of material release. The staff's analysis showed that the material release can be rapid; accordingly, the staff team concludes that self-protection is not a defensible mitigation strategy. Elsewhere in the defense nuclear complex, this type of accident is addressed with simple administrative controls such as a forklift spotter.

  The Board's staff team discussed this accident scenario during its teleconference with project personnel in October 2016. Project personnel communicated that all LANS work on risks associated with POCs in the TWF DSA was suspended in the fall of 2016 because the SER was expected to prohibit the receipt of POCs at TWF until performance testing of POCs is complete. Given that TWF is prohibited from receiving or storing POCs, there is no hazard at this time. Since the forklift tine puncture accident scenario can be addressed using administrative controls, the staff team does not expect a significant impact to the TWF control set by addressing this concern at a later date. As a result, the Board's staff plans to address this item during the next DSA revision, when risks associated with POCs can be discussed in detail.

- Radiolysis-Driven Drum Deflagration: In its CD-3 project letter, the Board expressed concern that the facility worker consequences for an accident involving a radiolysis-driven deflagration in the headspace of a drum (discovered to be damaged or otherwise not compliant with the WIPP waste acceptance criteria) were unanalyzed. The TWF DSA now captures the hazards associated with a deflagration of a noncompliant waste drum; however, the credited control assumes a degree of waste compliance, which is protected by the Radioactive and Hazardous Materials Shipping and Receiving Program rather than a Specific Administrative Control. The staff team plans to further assess the implementation of this program as part of transition to operations.

Fire Suppression System Freeze Protection (Status: Safety Observation)—The Board initially raised concerns related to freeze protection for the safety significant FSS in its 2012 CD-2 letter [8] related to the boundary of the credited system and reliability of the protection strategy. In particular, the communication link from TWF to the monitoring station and the equipment in the monitoring station for the TWF freeze protection equipment were not designed to be safety significant.

In the currently approved TWF DSA, the FSS is not identified as a safety significant control. Instead, the DSA credits an alternative control strategy relying primarily on administrative controls and a revised fire hazard analysis. During its evaluation of the facility SER, the SRB determined that the credited FSS was necessary to provide an adequate and defensible control set. This decision was documented in the TWF SER and implemented through COA 1, which states that "LANS shall revise the DSA and TSR to reclassify the FSS and minimum necessary, and sufficient support system(s) as SS [safety significant]. Revisions to the DSA and TSR shall be submitted for review and approval six months after Critical Decision 4 (Approve Start of Operations) or at first Annual Update, whichever occurs first [3]."

Given this decision, the boundary of the future safety significant system is not currently defined. The Board's staff team plans to review the revised DSA and control strategy against the guidance for freeze protection in the *Interim Guidance for Design and Operation of Wet Pipe Sprinkler Systems and Supporting Water Supplies* [9].

Newly Identified Safety Items. From its review of the final TWF safety basis, the Board's staff team identified additional concerns related to the hazard analysis, input assumptions, and facility control set. These new safety items are also summarized in Appendix A. The following sections provide additional details.

Combustible Loading Separation Distances (Status: Safety Observation)—The current TWF fire control strategy relies on combustible loading controls in the waste storage buildings (WSB) and the characterization and waste storage building (CWSB). The credited safety function of this control is to mitigate "the effects of an ordinary combustibles fire by reducing the heat flux such that TRU waste drums do not experience seal failure…." The Board's staff team's analysis identified two independent non-conservatisms in LANL's fire separation calculation that is used to justify the ability of the control to meet its safety function.

One non-conservatism is related to the use of a safety factor within the selected fire modeling technique (Mudan and Croce method), and the other is related to the calculation of the flame height. During the October interaction LANS personnel again stated that the calculation used the "realistic result" as allowed by the method for non-design applications, which does not require a safety factor. The staff team does not agree with using the "realistic result," because the project was designing the separation control to prevent drum seal failure, which requires the use of a safety factor to define a conservative separation distance.

Appendix B presents the staff team's independent analysis of separation distances to prevent the progression of a large facility fire. When a safety factor of two and a flame height adjustment are applied to the calculation, the number of drums damaged by the representative fire increases from zero to 21 drums. The resulting seal failures lead to calculated doses of 2.5 rem to the public and 57 rem to the co-located worker. For reference, the current mitigated analysis in the TWF safety basis calculates a dose of zero rem. The staff's calculation further indicates that increasing the separation distance by approximately 70 percent would prevent seal failure.

The Board's staff team notes that the resulting dose consequences do not approach levels that would require credited safety controls. However, as currently implemented, the control does not meet its safety function, to prevent seal failure during a fire. Furthermore, since similar separation strategies are used at other LANL facilities, the staff team believes that it would be prudent for LANL to perform an extent-of-condition review.

Fire Induced Structural Collapse (Status: Safety Observation)—The hazard analysis does not consider a large fire in a single WSB followed by a structural collapse. Assuming the consequences of this event are roughly one-sixth that of the seismic-fire event postulated to collapse all six buildings, this accident could challenge the evaluation guideline, with consequences exceeding 5 rem to the public.

The Board's staff team evaluated facility fires to determine the smallest fire likely to generate potential structural collapse conditions and assess the plausibility of the fire given the existing control set (see Appendix C). The Board's staff concluded that approximately 800 lbs of combustibles are necessary to sustain a fire large enough to challenge the 700 ˚C threshold on all the structural columns, which could then lead to structural collapse. This is well in excess of the existing transient combustible limit of 35 lbs. However, the result indicates that the combustible loading limits also implicitly serve to prevent thermally-induced structural collapse. Consequently, the staff team believes the description of the safety function should be updated to acknowledge and preserve this function.

Waste Storage Building Cladding (Status: Closed)—The TWF DSA credits the noncombustible exterior walls of the WSB and CWSB structures as a safety class control. The DSA describes their attributes and safety function as follows:

> *The specific attribute of the noncombustible exterior walls relied upon to protect this assumption is the fact that the WSB/CWSB walls are designed and constructed to prevent the spread of a fire between individual WSBs/CWSB and the spread of a fire from a characterization trailer in the Waste Storage Area to WSBs/CWSB. The safety function of the noncombustible walls is to mitigate the size of a fire such that it involves only individual WSBs/CWSB and prevents the spread of fire from one structure in the waste storage area to WSBs or the CWSB.*

The staff team's primary concern with the exterior walls' cladding was whether a wind event could shear the exterior wall off a TWF structure, exposing the interior to high wind and wind-borne missiles. This could lead to the ignition of a fire while compromising the control preventing fire from spreading between TWF structures.

In January 2017, LANS engineers provided calculations to demonstrate the natural phenomena hazards design category (NDC) 3 capacity of the exterior wall cladding and roof cladding for TWF building structures [10]. The Board's staff notes that the demand to capacity ratios for these elements is close to unity, and that an allowable stress increase of 1.5 was used, derived from American Institute of Steel Constructors' (AISC) N690-12, *Specification for Safety-Related Steel Structures for Nuclear Facilities*. The Board's staff notes that this increase is applicable for extreme wind events such as tornadoes, but not straight-line winds, which are defined as severe wind events with separate load combinations in the standard. For LANL, the design basis wind event is a straight-line wind, suggesting that this calculation is non-conservative, and that cladding may be damaged and compromised during an NDC-3 wind event at TWF. However, this postulated scenario requires multiple events to initiate a fire, which significantly reduces the associated risk. As a result, the Board's staff believes that the decrease in margin for wind performance of the cladding alone does not produce a significant radiological hazard for co-located workers or the public. Therefore, the Board's staff considers this item closed.

Summary. Since NNSA approval of the preliminary DSA in March 2014, LANS has developed and communicated roughly seven major iterations of the DSA. While iterations are expected, the significant oscillation in the selected control set between each revision was unusual for a defense nuclear facility's safety basis. This culminated in a request by LANS to pursue an alternative control strategy between the 95 percent and 100 percent drafts of the DSA in the summer of 2016.

The Board's staff has performed its own assessment of the TWF safety basis, and while a number of concerns remain, the Board's staff team concludes the approved control set is adequate for the approved scope of operations. The conditions imposed by the SER, including the direction to restore the FSS to safety significant and the prohibition of POCs, adequately mitigate the weaknesses in the DSA and controls. Once the DSA revisions are complete, the Board's staff plans to reevaluate the safety basis to assess whether it supports an expanded operating envelope (e.g., to enable TWF to receive TRU waste in POCs).

Cited References

[1] Los Alamos National Laboratory, *Documented Safety Analysis for Transuranic Waste Facility (TWF)*, DSA-TWF-001, Rev. 1, 100 percent Draft DSA, September 2016.

[2] Los Alamos National Laboratory, *Technical Safety Requirements for Transuranic Waste Facility (TWF)*, TSR-TWF-002, Rev. 1, 100 percent Draft TSRs, September 2016.

[3] National Nuclear Security Administration Los Alamos Field Office, *Safety Evaluation Report*, SER TA-63, Transuranic Waste Facility, Rev. 0, December 2016.

[4] Los Alamos National Laboratory, *Transuranic Waste Facility (TWF) Documented Safety Analysis*, DSA-TWF-001, Rev. 1, Final DSA, November 2016.

[5] Los Alamos National Laboratory, *Technical Safety Requirements for Transuranic Waste Facility (TWF)*, TSR-TWF-002, Rev. 1, Final TSRs, November 2016.

[6] Defense Nuclear Facilities Safety Board, *Critical Decision 3 Project Letter*, Letter to National Nuclear Security Administration with Enclosure, August 2014.

[7] Los Alamos National Laboratory, *Preliminary Documented Safety Analysis—Transuranic Waste Facility*, 102355-PDSA-001-R3.1, March 2014.

[8] Defense Nuclear Facilities Safety Board, *Critical Decision 2 Project Letter*, Letter to National Nuclear Security Administration with Enclosure, June 2012.

[9] National Nuclear Security Administration, *Interim Guidance for the Design and Operation of Wet Pipe Sprinkler Systems and Supporting Water Supplies*, March 10, 2010.

[10] Los Alamos National Laboratory, *TWF Storage Buildings Roof and Walls and Wind Generated Missiles*, ES-DO-17-006, January 18, 2017.

Appendix A

Summary of Safety Items with the Transuranic (TRU) Waste Facility (TWF) Project

Table A-1 – Previously Communicated Safety Items

Item	Status	Bounding Accidents	Credited Controls	Staff Commentary
Sealed Sources Pressurized Release	Closed	Sealed Sources Pressurized Release in Calibration Source Storage Building	Safety Class (SC) – Fire Rated Safes	The Board's staff has identified concerns related to the effectiveness of the fire watch used to protect sources in the characterization trailers and how it is currently documented in the documented safety analysis (DSA). However, given the limited time that the sources will be at risk (they are used only to calibrate the machine and then stored in a credited safe), the fire watch SAC, combined with the fire-rated safes (for storage) are an adequate control set.
		Sealed Sources Pressurized Release in High Efficiency Neutron Counter	Specific Admin. Control (SAC) – Fire Watch	
Site Specific Deposition Velocity	Closed	Various		The staff has reviewed the site-specific dispersion analysis and agrees that the 0.4 centimeter per second (cm/s) deposition velocity value is appropriate for TWF.

Table A-1 – Previously Communicated Safety Items

Item	Status	Bounding Accidents	Credited Controls	Staff Commentary
Fire Suppression System (FSS) Freeze Protection	Safety Observation	Large Facility Fire (Forklift fire)	Safety Significant (SS) – FSS	This item is moot so long as the FSS is not safety significant, and should be reassessed once the DSA is revised. The boundary of the safety significant FSS (as previously defined) is insufficient to protect the system during freezing weather. The last documented strategy relies on using an uncredited communications loop between the safety system and the Emergency Operations Center to inform personnel of freezing conditions in the wet portions of the system. It should be noted that the required FSS water supply level alarm suffers the same limitation as freeze protection.
Facility Worker Safety Analysis	Part 1: Safety Observation	Forklift tine puncture of POC	None credited	There are multiple concerns related to pipe overpack containers (POCs) that have not been addressed in the DSA at this time. There is a condition of approval in the Safety Evaluation Report (SER) prohibiting POCs at TWF until the DSA is updated to resolve an unrelated item. The staff plans to reengage with the facility once that effort is underway.

Table A-1 – Previously Communicated Safety Items

Item	Status	Bounding Accidents	Credited Controls	Staff Commentary
	Part 2: Safety Observation	Drum deflagration in suspect container	SS – TRU Waste containers (including vent)	The TWF DSA now captures the hazards associated with a deflagration of a noncompliant waste drum; however, the credited control assumes a degree of waste compliance, which is protected by the Radioactive and Hazardous Materials Shipping and Receiving Program rather than a SAC. The staff team plans to further assess the implementation of this program as part of transition to operations.
Safety Classification of Non-combustible Roofs	Closed	Wildland fire impacts TWF	SC – Non-combustible roofs	The DSA has adequately captured this control.

Table A-2 – Newly Identified Safety Items

Item	Status	Bounding Accidents	Controls	Staff Commentary
Combustible Loading Separation Distances	Safety Observation	Combustible fire in Waste Storage Building (WSB) or Characteriz a-tion and Waste Storage Building	SAC – Indoor Combustible Loading Separation	The consequences of this accident do not approach levels which would require credited safety controls. However, the staff's supporting calculation concludes that the fire hazard analysis for TWF improperly calculates the required separation distances between fuel packages and waste drums. As such, the existing control likely will not meet its intended safety function.

Table A-2 – Newly Identified Safety Items

Item	Status	Bounding Accidents	Controls	Staff Commentary
Fire Induced Structural Collapse	Safety Observation	Large combustible fire leading to structural collapse of a WSB	N/A	The DSA does not analyze a structural collapse brought on by a large fire within a storage building. As the dose consequences of this event could challenge the evaluation guideline, the staff performed an independent analysis to assess the likelihood of this event. While ultimately unlikely, the staff cannot conclude that this event is incredible; and therefore, it should be included in the TWF hazard analysis.
Waste Storage Building Cladding	Closed	Prevents the spread of fire from one building to another	SC – Non-combustible wall construction	The safety basis does not adequately capture the performance criteria of the building cladding credited to help prevent the spread of a fire from building to building. While the Board's staff does not believe there is sufficient design margin in the cladding to guarantee functionality after a design basis wind event, there are adequate defense in depth controls to control the potential accident.
SACs	Closed	Fuel-pool fire in the shipping and receiving area	SAC – TWF Site Fueled Vehicle Restriction SS – Site Drainage	The Board's staff had concerns that previous versions of the DSA credited only the SAC to prevent this accident. Based on an independent analysis by the staff team and the addition of the site drainage to the control set, the team considers the controls to be adequate.

Table A-2 – Newly Identified Safety Items

Item	Status	Bounding Accidents	Controls	Staff Commentary
Structural Quality Assurance	Closed	Wind or snow natural phenomena hazards (NPH) event causing structural collapse and fire	SC – NPH Building Design	The Board's staff had multiple concerns related to the quality assurance of the building structure. After an independent assessment, the team considers the structural design sufficient to perform its function.
Building Separation Distances	Closed	Combustible fire spreading between or from characteriza-tion trailers	No longer a credited control – treated as an initial condition	The Board's staff had concerns related to the adequacy of the calculations supporting the building separation distances between the trailers and the waste buildings. After reviewing the latest fire hazard analysis, the team considers these distances sufficient.
Wildland Fire Analysis	Closed	Wildland fire impacting TWF	SAC – Outdoor Combustible Loading Control	This item was related to the separation distances between characterization trailers. With the adequate response to that item and the addition of the outdoor combustible loading SAC, the team considers this item adequately addressed.
Unanalyzed Vehicle Accidents	Closed	Offsite vehicle bypassing the offsite vehicle barriers	SC – Offsite Vehicle Barriers SC – Onsite Vehicle Barriers SAC – TWF Site Fueled Vehicle Restriction	The 90 percent draft DSA provided sufficient documentation to conclude that the previously made "torturous path" argument was technically defensible.

Appendix B

Engineering Calculation: Fire Separation Distances

This appendix presents the body of Engineering Calculation EC.FY17.NFDI.LANL. TWF.FireSeparationWaste, *Evaluation of Representative Fuel Package Separation at the Transuranic Waste Facility* [B-1]. Two attachments describing the spreadsheets used in this calculation are available in the documented calculation, but are not provided in this appendix for brevity.

1. Background and Objective

The Transuranic Waste Facility (TWF) is a new construction Hazard Category 2 nuclear facility designed to be Los Alamos National Laboratory's (LANL) new facility for the storage, characterization, and intra-site shipping of newly generated transuranic (TRU) waste. The current TWF fire control strategy relies on combustible loading controls in the Waste Storage Buildings (WSB) and Characterization and Waste Storage Building (CWSB) to prevent the progression of a large facility fire. During its assessment of the control's efficacy in 2016, the Board's staff identified a potential non-conservatism in the calculated separation distances between representative fuel packages (RFPs) and the material-at-risk (MAR).

The non-conservatism relates to the use of an appropriate safety factor in the Mudan and Croce method, which is used to determine the fire separation distances in a LANL calculation applied to TWF (hereafter referred to as the "LANL calculation") [B-2]. The Mudan and Croce method, which is described in the Society of Fire Prevention Engineers (SFPE) Handbook [B-3], estimates the radiant heat flux to a target from a source fire. The separation distances are calculated by determining the minimum separation distance between and RFP and MAR that prevents development of radiant heat fluxes associated with waste drum seal failure or lid loss. The SFPE Handbook recommends that a safety factor of two be used with this method:

> *A safety factor of 2 is recommended for use with the Mudan and Croce method. Figure 3-10.38 is a comparison of predicted and measured heat fluxes with the inclusion of the recommended factor of safety. Figure [3-10.38] clearly shows that essentially all the data are over predicted by the Mudan and Croce model with a safety factor of 2. The safety factor of 2 is a recommendation for use in design applications. Where a realistic result is required, no safety factor should be applied."* [Bracketed figure number above corrects error in original text.]

Figure B-1 shows the predicted and measured heat fluxes from the Mudan and Croce method. Note that without the safety factor, there are a number of data points where the Mudan and Croce method under predicts the radiant heat flux. Using a safety factor of 2 ensures that nearly all of the data points fall in the over predicted region. The LANL calculation [B-2] does not appear to incorporate an explicit safety factor as suggested by the method, and no discussion of this safety factor is provided in the calculation.

The TWF Safety Evaluation Report [B-4] directed the restoration of the safety significant fire suppression system as a credited control; therefore the separation distances between RFPs have become less of a concern. The Board staff's remaining concern is the separation of an RFP from the MAR in a WSB. The objective of this calculation is to evaluate the radiant heat flux from a burning RFP to the nearby MAR (waste drums) with a safety factor of two and determine if the current control set is adequate.

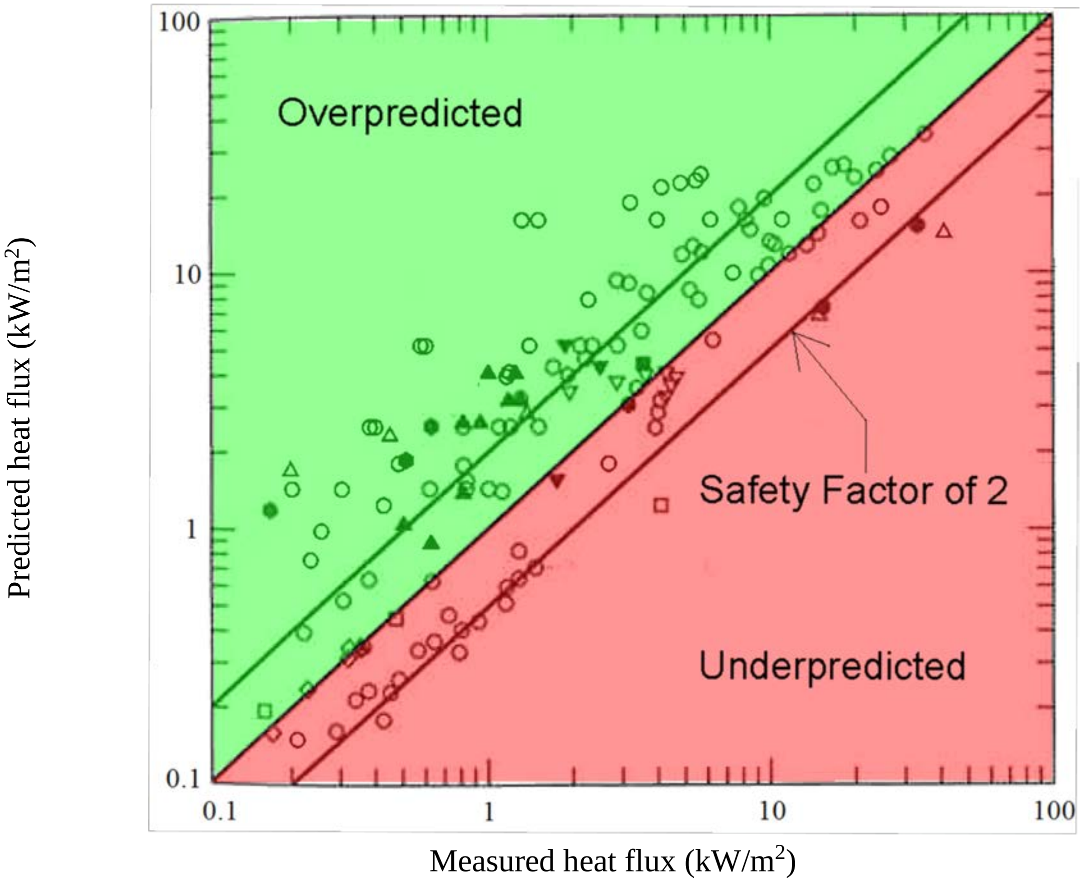

Figure B-1. *Empirical vs. Predicted Heat Flux Values (Source:* ***SFPE*** *Handbook, 3rd Edition, 2002 [B-3])*

During the development of this calculation, the Board's staff examined a potential item with the methodology used in the LANL calculation [B-2]. The flame height associated with the burning RFP in the LANL calculation is taken as the flame height generated by a fire with the same footprint area as an RFP, plus the height of the RFP. The technical basis for the addition of the RFP height to the flame height is not presented in the LANL calculation. Flame height equations used in typical fire analyses are taken from the base of the fire, not the top of the burning object. This includes the flame height equation used in the Mudan and Croce method. Since flame heights are proportional to fire heat release rates, the flame heights used in the LANL calculation may not be representative of the fire heat release rates specified for the RFPs. A second objective for this calculation is to determine if the flame heights used in the LANL calculation are consistent with the heat release rates prescribed for RFPs in the LANL calculation. If the flame heights are consistent with fires *smaller* than those prescribed in the LANL calculation for RFP heat release rates, the resulting radiant heat flux will be smaller, leading to potentially inadequate separation distances. In that case, this calculation will apply a sample adjustment to determine if there is a potential need to adjust the control set for TWF.

The approach taken in this evaluation is to calculate the radiant heat flux to the MAR (waste drums); determine how many drums are above the threshold for seal failure or lid loss; and estimate the expected doses to the public and co-located worker based upon the number of impacted drums.

2. Assumptions and Input Parameters

Several inputs are taken directly from the LANL calculation [B-2]:

1. RFP length:	0.61 m (2.0 ft)
2. RFP width:	0.30 m (1.0 ft)
3. RFP height:	0.91 m (3.0 ft)
4. RFP equivalent pool fire mass loss rate:	0.0144 kg/m^{2}sec (0.00294 lb/ft^2·sec)
5. RFP heat of combustion:	18,600 kJ/kg (38,800 BTU/lb)
6. Ambient air density:	1.2 kg/m^3 (0.075 lb/ft^3)
7. Threshold exposure for drum counting:	33 percent

The threshold exposure for drum counting (Input 7) is the percentage of drum height that must be exposed to the target heat flux before it is counted as exposed. This prevents over counting drums when the target heat flux only occurs on a very small portion of a particular drum.

The RFPs included in this evaluation are 11.4 kg (25 lb) and 15.9 kg (35 lb), as utilized in the Technical Safety Requirements [B-5] and Fire Hazards Analysis [B-6]. The fire heat release rates of these RFPs are 546 kW (518 BTU/sec) and 763 kW (723 BTU/sec), respectively.

The target radiant heat fluxes used in this evaluation are 15.9 kW/m^2 (1.4 BTU/sec·ft^2) [B-7] and 45 kW/m^2 (4.0 BTU/sec·ft^2) [B-2]. These heat fluxes are consistent with drum seal failure and drum lid loss, respectively.

Several assumptions are applied to the calculation, including the geometry of the stacked waste drum array. Figure B-2 shows the geometry used in the model. Assumptions in this calculation:

1. Drum dimensions (typical dimensions for a U.S. 55-gallon drum are used):

   a. Diameter: 57 cm (22.5 in),
   b. Height: 84 cm (33 in), and
   c. Drum nodes: 12 (over the height of each drum).

2. Pallet dimensions (typical pallet for drum storage):

   a. Width: 1.2 m (4.0 ft),
   b. Depth: 1.2 m (4.0 ft), and
   c. Height: 15 cm (6.0 in).

3. Gap between pallet stacks is 2.5 cm (1.0 in). This is a nominal amount of space included for manual pallet maneuvering.

4. Four drums are centrally positioned on a pallet, with all drums touching and an equidistant gap between the drums and the pallet edge.

5. Three tiers of pallets and drums are in each stack.

6. Nine pallet stacks are evaluated, with the fire in line with the left drums of the center stack.

7. Atmospheric transmissivity is equal to unity, which is conservative as losses to the atmosphere are ignored.

8. Pallets are transparent to radiation so the heat flux to the drum faces is maximized.

9. Terms used in the calculation of doses to the public and co-located worker:

   a. MAR: 80 PE-Ci per drum, per the TWF Documented Safety Analysis [B-8],

   b. DR: 0.5 for 10 or more drums, 1.0 for less than 10 drums, per DOE Standard 5506 [B-7],

   c. ARF×RF: 5×10^{-4} [B-8],

   d. LPF: 1 (conservative value as it is the maximum),

   e. $\chi/_Q$: 9.59×10^{-5} sec/m^3 (2.72×10^{-6} sec/ft^3) for the public [B-8], 3.5×10^{-3} sec/m^3 (9.9×10^{-5} sec/ft^3) for the co-located worker [B-8] (both of these values are specific to LANL),

   f. DCF: 1.85×10^{8} rem/PE-Ci for the public (International Commission on Radiological Protection (ICRP) Publication 72) [B-9], 1.18×10^{8} rem/PE-Ci for the co-located worker (ICRP Publication 68) [B-10], and

   g. BR: 3.3×10^{-4} m^3/sec (1.2×10^{-2} ft^3/sec) [B-8].

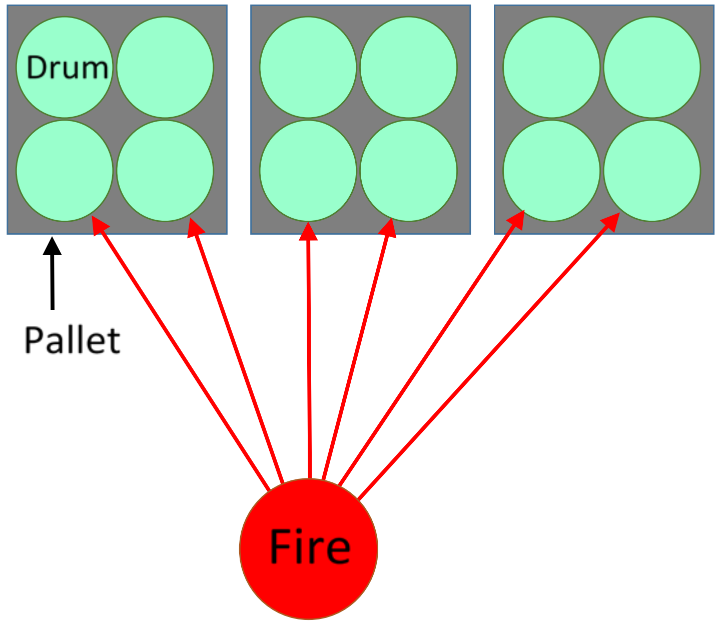

Figure B-2. *Plan view of the calculation geometry*

3. Analytical Methods and Computations

The Mudan and Croce method [B-3] is used to calculate the radiant heat flux from the fire to the drums. This method, which is used in the LANL calculation [B-2], is based on the following equation:

$$\dot{q}'' = f_s E F \tau \quad \text{Eq. B-1}$$

where E is the average emissive power (kW/m^2),

F is the view factor between the target and the flame (non-dimensional),

τ is the atmospheric transmissivity (non-dimensional), and

f_s is a safety factor (considered to be 1 in the LANL calculation).

The fire emissive power is a function of the fire diameter (D_h in m):

$$E = 140e^{-0.12D_h} + 20(1 - e^{-0.12D_h}) \quad \text{Eq. B-2}$$

The fire diameter in this calculation is the hydraulic diameter, which is based on the floor area (A in m^2) of the fire:

$$D_h = \sqrt{\frac{4A}{\pi}}$$ **Eq. B-3**

A cylinder with a height equal to the flame height represents the flame in this method. The radiation view factor geometry is shown in Figure B-3. The following equation calculates the view factor, applying view factor geometry as appropriate for the height under consideration:

$$F = \frac{1}{\pi S}\tan^{-1}\left(\frac{h}{\sqrt{S^2-1}}\right) - \frac{h}{\pi S}\tan^{-1}\left(\sqrt{\frac{S-1}{S+1}}\right) + \frac{Ah}{\pi S\sqrt{A^2-1}}\tan^{-1}\left(\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}}\right)$$ **Eq. B-4**

where $S = 2L/D_h$

$h = 2H_f/D_h$, and

$$A = \frac{h^2 + S^2 + 1}{2S}$$

The following equation calculates the flame height in the Mudan and Croce method:

$$H_f = 42D_h\left(\frac{\dot{m}''_\infty}{\rho_a\sqrt{gD_h}}\right)^{0.61}$$ **Eq. B-5**

where $\dot{m}''_\infty$ is the mass burning rate per unit area (kg/m^2·sec),

ρ_a is the ambient air density (kg/m^3), and

g is acceleration of gravity (9.81 m/sec^2).

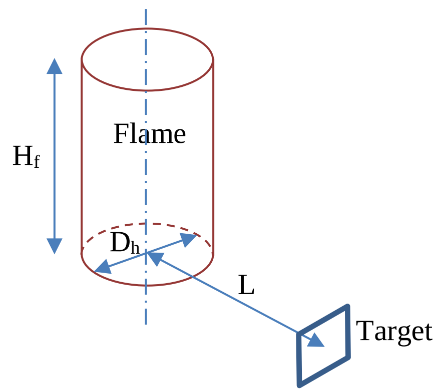

Figure B-3. *View factor geometry*

In the LANL calculation [B-2], the height of the RFP is added to the flame height calculated in Eq. B-5 above to get the total flame height:

$$H_f = 42D_h\left(\frac{\dot{m}''_{\infty}}{\rho_a\sqrt{gD_h}}\right)^{0.61} + H_{RFP} \qquad \textbf{Eq. B-6}$$

where, H_{RFP} is the height of the Representative Fuel Package (m). As noted in Section 1, the LANL calculation does not describe a technical basis for this addition. This flame height determination method is repeated in this calculation for comparison purposes.

The distance between the fire and the drum face (*L* in Figure B-3) is calculated from the geometry between the drum pallet stacks and the fire. This geometry is shown in Figure B-4, and calculated as follows:

$$L = \sqrt{x^2 - y^2} - \frac{D_{drum}}{2} \qquad \textbf{Eq. B-7}$$

In each scenario, the radiant heat flux is calculated at each height position on each drum in the full array using the above methods. Twelve equidistant height positions are included for each drum. This number is selected because 12 points will provide sufficient resolution of heat flux on each drum. A drum is counted as exposed if 33 percent of its height receives greater than the target flux (four of twelve height positions). The number of drums in each stack exceeding the thresholds is counted, then the counts for the stacks are summed.

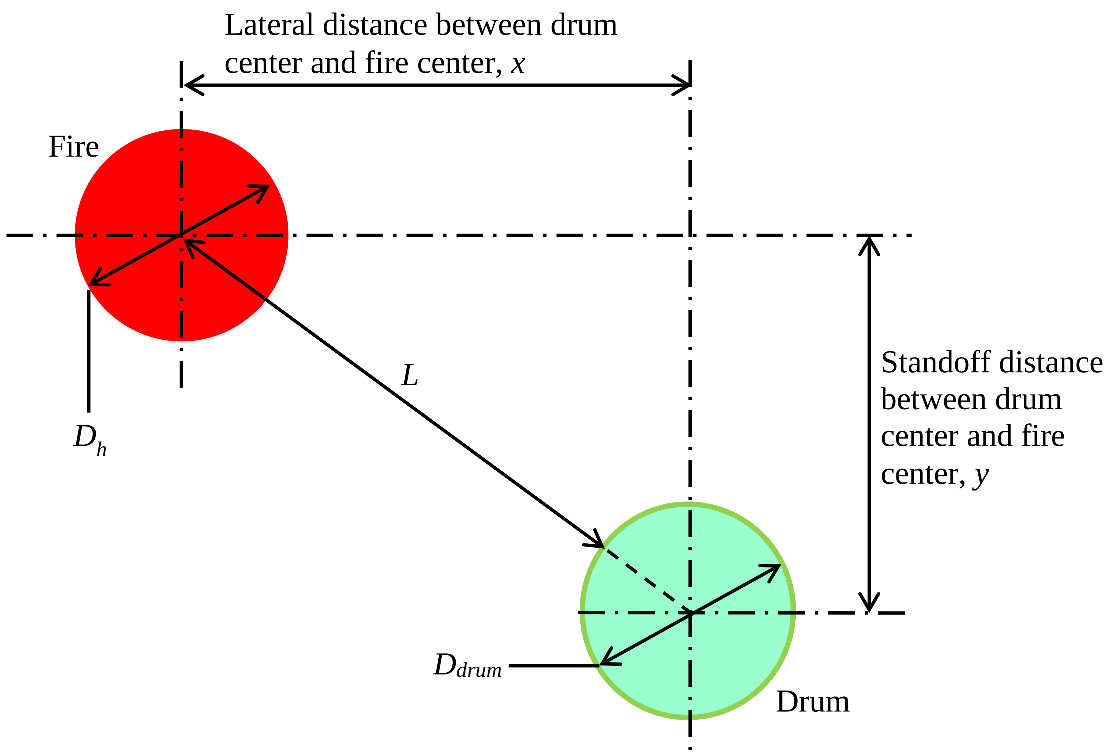

Figure B-4. *Geometry between the fire and drum*

As noted in Section 1, there are potential issues with calculating the flame height using Eq. B-6 in the LANL calculation. A potential alternate method of calculating flame height of a burning RFP is to use a flame height equation that is based only on the fire heat release rate and the effective fire diameter. Such an equation appears in the 5th edition of the SFPE Handbook of Fire Protection Engineering [B-11]:

$$H_f = 0.235\dot{Q}^{2/5} - 1.02D_h \qquad \text{Eq. B-8}$$

where $\dot{Q}$ is the heat release rate of the fire (kW) and D_h is the hydraulic diameter of the fire. This equation may be solved for $\dot{Q}$ to estimate the effective fire heat release rate, using the flame height and RFP fire diameter from the LANL calculation:

$$\dot{Q} = \left(\frac{H_f + 1.02D_h}{0.235}\right)^{5/2} \qquad \text{Eq. B-9}$$

If the effective fire heat release rate calculated with Eq. B-9 is less than RFP heat release rates prescribed by the LANL calculation, a sample adjustment will be applied to the separation distance calculation method represented by Equations B-1 to B-7. If the effective heat release rate is larger than the prescribed RFP heat release rates, the LANL calculation is conservative and this calculation will not consider an adjustment, other than the safety factor as already discussed.

If applied, the sample adjustment will use Eq. B-8 to determine a flame height from the RFP fire diameter and the prescribed heat release rate for the RFP (i.e., 546 and 763 kW (518 and 723 BTU/sec)) in lieu of either Eq. B-5 or B-6. The radiant heat flux to the drums will then be calculated as before, with the new flame height applied. Note that this is only one potential method of adjustment to the LANL calculation. It was selected for convenience and simplicity because it easily fits within the framework of the LANL calculation methodology. In terms of this calculation, the primary objective is determining the potential need to alter the TWF control set. Other adjustment methods, such as determining an equivalent pool fire or applying another fuel package such as wood cribs or trash bags, could be used as an adjustment. However, these evaluations are beyond the scope of the current calculation.

The dose to the public and co-located worker is calculated using the following equation from DOE Standard 5506 (in rem) [B-7]:

$$Dose = ST \times \left(\chi/Q\right) \times DCF \times BR \qquad \text{Eq. B-10}$$

where *ST* is the respirable source term (PE-Ci),

χ/Q is the atmospheric dilution factor (sec/m^3),

BR is the breathing rate (m^3/sec), and

DCF is the inhalation dose conversion factor (rem/PE-Ci).

The equation for the source term is:

$$ST = MAR \times \#\,Drums \times DR \times (ARF \times RF) \times LPF \qquad \text{Eq. B-11}$$

where *MAR* is the amount of radionuclides available to be acted on by a given physical stress (PE-Ci),

 # Drums is the number of affected drums from the heat flux calculation,

DR is the damage ratio or fraction of the MAR that is impacted by the postulated accident scenario (non-dimensional),

ARF is the airborne release fraction (non-dimensional),

RF is the respirable fraction (non-dimensional), and

LPF is the leak-path factor (non-dimensional).

4. Results

Four scenarios are considered in this evaluation, which are shown in Table B-1. These scenarios vary the RFP size and application of a safety factor to the Mudan and Croce method. Table B-2 presents the results of the scenarios, including the calculated effective heat release rate. Comparing the prescribed RFP heat release rate in Table B-1 with the effective heat release rate shown in Table B-2 shows that the effective heat release rate in the LANL calculation is only about 50 percent of the prescribed RFP heat release rate. As noted in Section 3, an effective heat release rate lower than the prescribed heat release rate will result in separation distances that are too small. Therefore, a flame height consistent with the prescribed heat release rate is applied as a sample adjustment. The results are shown in Table B-2 under the “Adjusted Calculation” heading. In the adjusted cases with no additional safety factor, four drums are exposed to heat fluxes associated with drum seal failure. This result applies to both the 11.4 kg (25 lb) and 15.9 kg (35 lb) RFPs. The corresponding dose to the public is < 1 rem, while the dose to the co-located worker is about 22 rem. Even without considering a safety factor, separation distances must be increased by about 10 percent to prevent exposing any drums to 15.9 kW/m² (1.4 BTU/ft²sec) (see Table B-3).

Applying a safety factor of two results in exposing a larger number of drums to heat fluxes that can induce seal failure. Even without applying the flame height adjustment, 10 drums are exposed, resulting in doses similar to those described above (see Table B-2, under the “LANL Calculation” header). When both the safety factor and flame height adjustment are applied to the calculation, the number of exposed drums rises to 19 and 21 for the 11.4 kg (25 lb) and 15.9 kg (35 lb) RFPs, respectively. The doses range from 2 to 2.5 rem to the public, and 52 to 57 rem to the co-located worker, for the smaller and larger RFP, respectively. With a safety factor of two, separation distances must be increased by about 80 percent to prevent exposing any drums to 15.9 kW/m² (1.4 BTU/ft²sec) (see Table B-3).

The LANL calculation does not explicitly include a safety factor in the Mudan and Croce method. However, some conservatism is included in the development of the prescribed heat release rates for the RFPs. For a single RFP, the LANL calculation assumes all six sides of the RFP burn and contribute to the heat release rate. Because one side faces the floor, only five sides actually contribute to the heat release rate. Based on the geometry of the RFP presented in Section 2, only 1.86 m^2 (20.0 ft^2) of 2.04 m^2 (22.0 ft^2) of the RFP surface area is exposed for burning. This reduction implies a safety factor of 1.1. This safety factor can be combined with the safety factor used in the Mudan and Croce method to achieve an overall safety factor of two. In this case, the Mudan and Croce method only requires application of a safety factor of 1.8 instead of two (i.e., $1.1 \times 1.8 = 2$). The resulting difference in separation distances from this exercise is shown in Table B-3. The use of a safety factor of 1.8 in the Mudan and Croce method results in a required separation distance increase of about 70 percent instead of about 80 percent to achieve a safety factor of two.

Table B-1. *Fire Scenarios and Inputs*

Input		Representative Fuel Package (RFP) kg [lbs]			
		11.4 [25]	11.4 [25]	15.9 [35]	15.9 [35]
Prescribed RFP Heat Release Rate[1]	kW [BTU/sec]	546 [518]	546 [518]	764 [724]	764 [724]
Equivalent Pool Fire Diameter[2], D_h	m [ft]	0.49 [1.61]	0.49 [1.61]	0.58 [1.89]	0.58 [1.89]
Separation Distance from Fire Hazards Analysis[2] (Distance from flame edge to face of nearest drum)	m [ft]	1.19 [3.90]	1.19 [3.90]	1.40 [4.59]	1.40 [4.59]
Safety Factor applied to Mudan & Croce calculation	N/D	1	2	1	2

[1] Source: Table 3 in the LANL calculation [B-2]. Value for 35 lb RFP interpolated from table.
[2] Source: TWF Fire Hazards Analysis (FHA) [B-6]. Calculations presented in the FHA are based on the LANL calculation. Note that the LANL calculation does not contain a 35 lb RFP. This size RFP was developed by the FHA.

Table B-2. *Fire Scenario Results*

Result		Representative Fuel Package Size, kg [lbs] Safety Factor			
		11.4 [25] 1	11.4 [25] 2	15.9 [35] 1	15.9 [35] 2
LANL Calculation					
# Drums exposed to > than 15.9 kW/m² (1.4 BTU/ft²sec)[1]		0	10	0	10
Effective Fire Heat Release Rate	kW [BTU/sec]	288 [273]	288 [273]	355 [336]	355 [336]
Public Dose	rem	0	1.17	0	1.17
Co-Located Worker Dose	rem	0	27.26	0	27.26
Adjusted Calculation					
# Drums exposed to > than 15.9 kW/m² (1.4 BTU/ft²sec) [1]		4	19	4	21
Fire Heat Release Rate	kW [BTU/sec]	546 [518]	546 [518]	764 [724]	764 [724]
Public Dose	rem	0.94	2.22	0.94	2.46
Co-Located Worker Dose	rem	21.81	51.79	21.81	57.24

[1] No drums reach the threshold of 45 kW/m^2 (1.4 BTU/sec·ft^2) in these scenarios.

Table B-3. *Separation Distance Results*

Result		Representative Fuel Package Size, kg [lbs] Safety Factor					
		11.4 [25] 1	11.4 [25] 1.8	11.4 [25] 2	15.9 [35] 1	15.9 [35] 1.8	15.9 [35] 2
Separation Distances							
LANL Calculation Separation Distance	m [ft]	1.19 [3.90]	1.19 [3.90]	1.19 [3.90]	1.40 [4.59]	1.40 [4.59]	1.40 [4.59]
Required Separation Distance, 0 drums > 15.9 kW/m² (1.4 BTU/ft²sec) from adjusted calculation	m [ft]	1.33 [4.36]	2.02 [6.63]	2.16 [7.09]	1.55 [5.10]	2.33 [7.64]	2.50 [8.20]
Percentage increase in separation distance	%	12	70	82	11	66	79

5. Conclusions

The results of this evaluation lead to the following conclusions:

1. *The dose consequences to the public for all of the considered scenarios do not require consideration of safety class controls.* The maximum dose to the public is below 5 rem.

2. *The dose consequences to the co-located worker for all of the considered scenarios do not require safety significant controls.* However, the dose is between 20 and 60 rem to the co-located worker, depending on the scenario. At this exposure level, safety significant controls could be considered. The control set for TWF includes a specific administrative control for indoor combustible loading, which specifies separation distances according to the LANL calculation. This type of control is appropriate for protecting the co-located worker, but should be updated to include more conservative separation distances that address deficiencies in the LANL calculation. Suggested separation distances are 2.0 m (6.5 ft) for 11.4 kg (25 lb) RFPs, and 2.3 m (7.5 ft) for 15.9 kg (35 lb) RFPs, which is consistent with the application of a 1.8 safety factor to the Mudan and Croce method.

3. The *LANL calculation should be more thoroughly reviewed by the Board's staff.* The Board's staff confirmed that the RFP flame heights in the LANL calculation were too low, resulting in smaller separation distances. The LANL calculation is also used as a basis for one of the requirements in Technical Area 54, Area G Technical Safety Requirements [B-12] and may be used for other safety basis analyses at LANL. The LANL calculation also includes sections on crate fires and pool fires that were not addressed by this calculation. The Board's staff should consider: 1) determining the extent to which the LANL calculation is used in safety basis development at LANL, and 2) reviewing the other parts of the calculation, given the deficiencies found in regards to representative fuel packages.

6. References

[B-1] Defense Nuclear Facilities Safety Board (DNFSB), *Evaluation of Representative Fuel Package Separation at the Transuranic Waste Facility*, Revision 0, EC.FY17.NFDI.LANL.TWF.FireSeparationWaste, Washington, D.C.: DNFSB, June 2.

[B-2] Los Alamos National Laboratory, *Calculation for Radiant Energy at a Distance Away from Object for "Ordinary" Combustibles and Pool Fires*, Revision 1, SB-DO:CALC-11-014, Los Alamos, NM: Los Alamos National Laboratory, June 21, 2011.

[B-3] C. Beyler, Chapter 11, "Fire Hazard Calculations for Large, Open Hydrocarbon Fires," in *SFPE Handbook of Fire Protection Engineering*, 3rd ed., Quincy, MA, National Fire Protection Association, 2002.

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[B-5] Los Alamos National Laboratory, *Technical Safety Requirements for Transuranic Waste Facility (TWF)*, Revision 1, TSR-TWF-002, Los Alamos National Laboratory, Los Alamos, NM, November 2016.

[B-6] Los Alamos National Laboratory, *Fire Hazard Analysis, TRU Waste Facility (TWF) Project*, Revision 9, 102355-HA-00001, Los Alamos, NM, November 2016.

[B-7] Department of Energy, *DOE Standard, Preparation of Safety Basis Documents for Transuranic (TRU) Waste Facilities*, DOE-STD-5506-2007, Washington, DC: Department of Energy, April 2007.

[B-8] Los Alamos National Laboratory, *Transuranic Waste Facility (TWF), Documented Safety Analysis*, Revision 1, DSA-TWF-001-R1, Los Alamos, NM, November 2016.

[B-9] International Commission on Radiological Protection, *Age-dependent Doses to the Members of the Public from Intake of Radionuclides - Part 5 Compilation of Ingestion and Inhalation Coefficients*, ICRP Publication 72, 1995.

[B-10] International Commission on Radiological Protection, *Dose Coefficients for Intakes of Radionuclides*, ICRP Publication 68, 1994.

[B-11] G. Heskestad, Chapter 13, "Fire Plumes, Flame Height, and Air," *SFPE Handbook of Fire Protection Engineering*, 5th ed., New York, NY, Springer Science+Business, 2016.

[B-12] Los Alamos National Laboratory, *Technical Safety Requirements (TSRs) for Technical Area 54, Area G*, Rev. 3.3, ABD-WFM-002, Los Alamos National Laboratory, Los Alamos, NM, December 2015.

Appendix C

Engineering Calculation: Fire-Induced Structural Collapse

This appendix presents the body of Engineering Calculation EC.FY17.NFDI.LANL.TWF.StructuralFire, *Structural Fire Analysis of a Waste Storage Building at the Transuranic Waste Facility* [C-1]. Several attachments identified in the body of the calculation are available in the documented calculation, but are not provided in this appendix for brevity.

1. Background and Objective

The accident analysis section of the Transuranic Waste Facility (TWF) documented safety analysis (DSA) considers a seismic event followed by a fire encompassing all six waste storage buildings (WSB) and the Calibration Source Storage Building (CSSB) (Hazard Scenario 7-007b) [C-2]. The unmitigated consequence to the maximally exposed offsite individual for this scenario is approximately 41 rem. The consequence is mitigated using a safety class switch that cuts electrical power during a seismic event, minimizing the possibility of multiple fire ignitions from electrical sources.

The hazard analysis does not consider a large fire in a single WSB followed by a structural collapse, which could challenge the evaluation guideline with a consequence in excess of 5 rem, with the co-located worker potentially exposed to a dose consequence in excess of 100 rem. As there is no seismic activity in this accident scenario, the consequences are not mitigated by the cutoff switch discussed above, and there are no alternative safety class engineered controls identified in the DSA.

Table 3 of the TWF Fire Hazard Analysis (FHA) [C-3] states that the International Building Code [C-4] construction type for the WSBs is Type IIB. This construction type is non-combustible but does not require structural members to have fire protection ratings. The FHA does not provide further discussion of structural fire protection. Given the lack of structural fire protection, the Board's staff questioned whether the control set was sufficient to address this particular fire scenario and prevent structural collapse. Note that the construction type selected for the storage buildings provides basic code-compliance. The Board staff's concern arises from a TWF safety analysis standpoint.

During previous discussions, project personnel communicated that they did not believe that a fire sufficient to challenge the structural integrity of the buildings was credible. They informally suggested they could document this engineering assessment in a later revision of the TWF FHA; however, they never developed this documentation. Given the potential dose associated with the accident, the Board's staff performed an independent technical assessment to determine the risk associated with this concern. This calculation documents the engineering evaluation used to assess this concern.

The objective of this evaluation is to analyze facility fires, determine the smallest fire likely to generate potential structural collapse conditions, and assess the plausibility of the fire given the existing control set. The facility fires considered develop from a plausible scenario of combustible material build-up over time, which then results in a fire that threatens the structural columns. The structural columns were selected for evaluation because they are directly exposed to the inside of the storage buildings. Two potential controls are available that could mitigate this scenario [C-5, C-6]:

- Fire Suppression System (to be restored to safety significant), and
- Indoor Combustible Loading Control (specific administrative control).

The fire suppression system is an engineered mitigative control that would limit the potential for fire spread and the maximum fire size, given ignition of combustibles. The combustible loading control is a mitigative specific administrative control that limits the potential fire size. Prevention of structural collapse from fire is not listed as a safety function of either control. If either control were diminished or eliminated in the future, the ability of the overall safety strategy to control this hazard scenario would be reduced. The fire scenarios considered here assume that both of these controls are ineffective (i.e., unmitigated scenarios).

A facility fire can always be postulated that will cause damaging conditions under the correct conditions. The focus of this analysis is to determine the smallest fire and the associated conditions (such as ventilation) that may allow the development of conditions conducive to structural collapse. The plausibility of this fire scenario can then be considered as well as the ability of available controls to prevent the fire scenario.

The approach taken in this evaluation is to first determine an upper structural column temperature that would be of concern from a potential collapse standpoint. Fire scenarios are then assessed to determine if these temperatures could reasonably be expected to develop in the columns as a result of fire. Intergraph GT STRUDL is used to evaluate the structural thermal effects, and CFAST is used to evaluate fire scenarios.

2. Assumptions and Input Parameters

<u>Structural Inputs</u>

The WSBs are simple steel moment frame structures supporting a roof structure of steel purlins and prefabricated roof panels. All structural columns are W12x65 shapes, with primary framing consisting of W14x30 sections with bolted moment frame connections. The analysis uses the latest revision of the WSB design to develop a representative two-dimensional frame, including section properties, boundary conditions, and dead loads [C-7]. The superimposed dead loads for TWF structures are derived from the dead load case shown below in Table C-1. These loads are then translated into purlin loads as shown in Table C-2. A graphic of the dead load distribution on the TWF Storage Building structure can be found in Attachment 1 of EC-FY17.NFDI.LANL.TWF.StructuralFire [C-1].

A National Institute of Standards and Technology (NIST) study of mechanical properties of structural steels from the World Trade Center disaster is used to determine the material properties of carbon steels under elevated temperatures [C-8]. This includes strength and stiffness relationships as a function of temperature. The ratio of yield stress at high temperatures compared to room temperature taken from this study can be seen in Figure C-1. The NIST

Model ("Model" line in Figure C-1) is based on Equation C-1 shown below. The NIST model for Young's Modulus is shown in Figure C-2 ("NIST 1" line) and the Shear Modulus and Poisson's ratio at elevated temperatures are provided in Appendix A. Equation C-2 is the basis for the NIST model in Figure C-2.

Table C-1. *Superimposed dead load from the original TWF structural design calculations [C-7]*

GRAVITY DESIGN LOAD SUMMARY -- ROOF LOADS

ITEM	DESCRIPTION	DECK DESIGN		PURLIN DESIGN		FRAME DESIGN	
DECK	1.5" Type B, 20 ga	2.5	PSF	2.5	PSF	2.5	PSF
INSULATION	6" Batt (1.1 psf per in)	6.6	PSF	6.6	PSF	6.6	PSF
ROOFING	22 gage standing seam	1.3	PSF	1.3	PSF	1.3	PSF
			PSF	0.0	PSF	0.0	PSF
			PSF	0.0	PSF	0.0	PSF
			PSF	0.0	PSF	0.0	PSF
PURLINS	@ 8'-0" o.c. (incl. in calculation)			0.0	PSF	2.8	PSF
M/E/P	Assumed (fp piping, sprinklers, lighting only)			2.0	PSF	2.0	PSF
CEILING	5/8" gyp board			2.8	PSF	2.8	PSF
					PSF		PSF
					PSF		PSF

	DECK DESIGN		PURLIN DESIGN		FRAME DESIGN	
DEAD LOAD TOTALS	10.4	PSF	15.1	PSF	17.9	PSF
ACTUAL VALUES USED	10.4	PSF	15.1	PSF	17.9	PSF
	MINIMUM		SNOW			
LIVE LOADS	30.0	PSF	34.8	PSF		

Table C-2. *Purlin Line Loads from original TWF structural design calculations [C-7]*

Building Length	64 ft	Purlin spacing	8 ft	
Building Width	33 ft	Girt Spacing	6.83 ft	
Eave Height	13.67 ft			
Ridge Height	15 ft			
# of Bays	4	For Wind:	a =	3.3 ft
		For Snow:		3.6 ft

Load Type	Load (psf)	Interior Purlins (lb/ft)	Exterior Purlins (lb/ft)
Dead	15.1	120.80	60.40
Live Roof	30	240.00	120.00
Snow Balanced	34.8	278.40	139.20

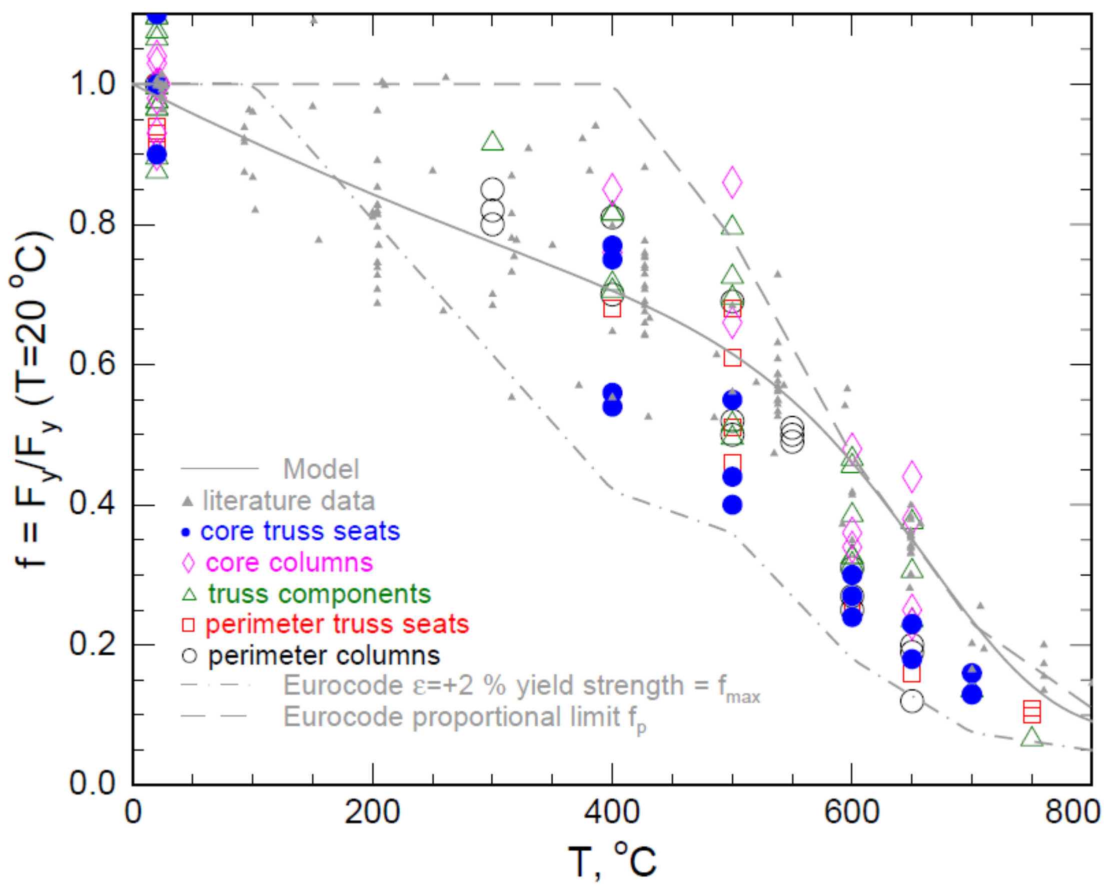


Figure C-1. *Ratio of yield strength of carbon steel at high temperatures compared to room temperature, from Figure 6-6 of the NIST report [C-8]*

$$f = \frac{F_y(T)}{F_y(23\ °\mathrm{C})} = (1 - A_2)\exp\left(-\frac{1}{2}\left[\left(\frac{T}{s_1}\right)^{m_1} + \left(\frac{T}{s_2}\right)^{m_2}\right]\right) + A_2 \qquad \textbf{Eq. C-1}$$

where $A_2 = 0.074692$,

$m_1 = 8.325929$,

$m_2 = 1.000000$,

$s_1 = 638.384277$ °C, and

$s_2 = 523.523132$ °C.

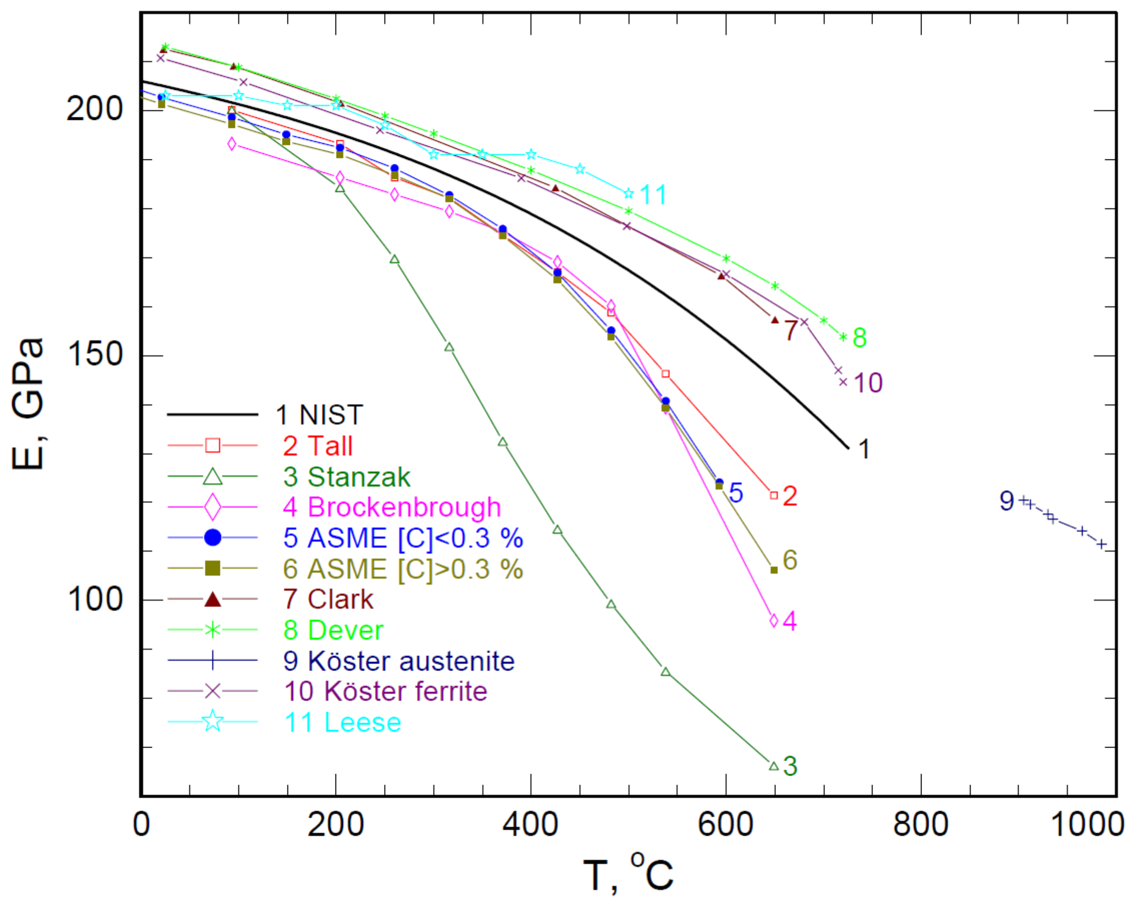


Figure C-2. *Modulus of Elasticity variation with temperature and NIST Model*

$$E(T) = e_0 + e_1 T + e_2 T^2 + e_3 T^3$$ **Eq. C-2**

where e_0 = +206 GPa,

e_1 = -4.326e-02 GPa/°C,

e_2 = -3.502e-05 GPa/°C^2, and

e_3 = -6.592e-08 GPa/°C^3.

Structural Assumptions

For the purposes of this structural calculation using the data above, the following assumptions are made in developing the structural model:

1. The structural load path is from the roof deck to the purlins, which then transfers load to the primary structural framing. The problem can be simplified to a two-dimensional representative portal frame with point loads at the location of purlin connections. The span width and node locations are copied from the TWF structural

design calculations, as are member section properties [C-7]. The line loads used for the interior and exterior purlins come from Table C-2.

2. For this analysis, only an unfactored dead load is considered. Live roof loads, snow loads, and lateral loads such as wind or seismic are not considered as concurrent. The load condition under fire is an extreme event; the likelihood of additional dead load concurrent with fire for a simple facility structure is low. Lateral loads can be resisted by unaffected columns through load transfer in the roof diaphragm since not all frames are affected by fire simultaneously, and the roof structure is insulated from the fire.
3. To ensure the worst case steel properties for the structural analysis model, data from the NIST report is used assuming the worst case steel properties for TWF columns at approximately 700 °C (1290 °F). Using Eq. C-1 provides a yield ratio of 0.23. However, there are data points that suggest potentially lower ratios of yield strength at 700 °C, so a ratio of 0.1 (10 percent yield strength remaining at 700 °C) was used for this calculation. The NIST equation for Young's Modulus (Eq. G-2) estimates a value of 136 GPa at 700 °C. For this calculation, Young's Modulus is taken to be 130 GPa (18,850 ksi). Steel properties beyond 700 °C (1290 °F) are not used due to the limited amount of empirical data beyond this temperature from the report.
4. While the NIST report provided relationships, for simplicity the lowest Shear Modulus provided by the NIST report at elevated temperatures is used (50 GPa [7,250 ksi]), as well as the largest Poisson's ratio (0.317). These reflect temperatures in excess of 700 °C but should not significantly affect this analysis. Figures of these values as well as their associated equations are provided in Attachment 2 of EC-FY17.NFDI.LANL.TWF.StructuralFire [C-1].
5. A Load Resistance Factor Design (LRFD) is used for checking stress values. GT STRUDL cannot readily perform a cold-based check using steel with 10 percent of its yield strength. Instead, the stress demand to capacity (D/C) ratios are compared to the yield strength ratio of steel at 700 °C to determine whether the columns are at risk of failure from dead load under elevated temperatures. For example, any D/C ratio using code-based checks exceeding 0.1 would exceed the remaining capacity in fire-degraded steel for the purposes of this calculation. Values below 0.1 would be considered to have margin to failure at 700 °C.
6. The roof beams and purlins are within the insulated ceiling cavity, and as such retain the stiffness properties of room temperature steels.
7. Deflections are expected to remain small even with lower stiffness of columns, with no significant non-linear geometric effects. This assumption will be confirmed by extracting the vertical deflection of the roof due to dead load.
8. Steel columns are unbraced lengths; no credit is given for the wall panels and support framing to brace TWF structural columns. The roof beams are braced laterally by the roof purlins out of plane.
9. Column to beam connections of the steel moment frame are assumed to be rigid, and there is no partial moment fixity at the baseplate connections.

Fire Modeling Inputs

The CFAST model geometry is based on the TWF design drawings for WSB 63-0149 [C-9, C-10, C-11, C-12, C-13, C-14, C-15, C-16]. Figure C-3 illustrates the interior of a typical WSB. The electrical closet and fire riser room seen in the rear of the picture are not included in the model, as the main storage area is the space of concern, and these rooms are assumed to be normally closed. Reduction in the overall volume of the main storage space is also more conservative in regards to heating of the room air and surfaces. The ceiling height and width of the main storage room are maintained, while the length is shortened to account for the reduction in volume.

The main storage area of the WSB has a variable ceiling height. The roof has a peak parallel to the long axis of the building, and the floor slopes down from the back of the building to the front [C-11]. Since the slope of the ceiling and floor are shallow in the WSBs, the compartment modeled in CFAST is represented with an average ceiling height. The compartment dimensions used in the model are:

- Length: 18.4 m (60.4 ft)
- Width: 9.8 m (32.2 ft)
- Height: 4.1 m (13.4 ft)

The development of the CFAST WSB model considers three vents: two personnel doors and the large roll-up door on the south side of the building. The soffit of the large roll-up door is positioned 1 m (3.3 ft) below the ceiling as shown in Building Section A on Drawing Sheet A-3000 [C-11]. The dimensions of the vents in the model are:

- Personnel Doors: 0.9 m (W) x 2.1 m (H) (3.0 ft x 7.0 ft)
- Large Roll-Up Door: 4.9 m (W) x 3.1 m (H) (16.1 ft x 10.2 ft)

Concrete footers are located around the base of the columns. These footers limit the proximity of potential fire fuels to the columns and are included in the model. Per Drawing C55444, Sheet S-5010 [C-16], these footers are 0.6 m (2.0 ft) square. The minimum standoff distance between the web of the column and potential fuels is 0.3 m (1.0 ft).

Several building materials are incorporated into the model so that the heat transfer through surfaces is approximated. These materials include wall insulation, ceiling insulation, gypsum wallboard, concrete, steel, and wood. The walls of the WSBs are a composite structure consisting of outer metal insulated panels, mineral wool insulation, and gypsum board. The ceiling structure consists of mineral wool insulation and gypsum wallboard. The floor consists of concrete, while the columns are made of steel. The material properties and physical details are taken from the drawings and specifications and are documented in Table C-3.

Figure C-3. *Interior of typical Waste Storage Building, nearing completion of construction*

CFAST version 7.2.1 [C-17] permits only a single material to be specified for floors, walls, and ceilings. Therefore, the material properties for the walls and ceilings are combined for input in the model. The process used to derive the combined inputs for thermal conductivity, specific heat, and density is described in Attachment 2 of EC.FY17.NFDI.LANL.TWF.StructuralFire [C-1]. Emissivity is taken as the emissivity of the inner surface, which is gypsum wallboard for the ceiling and walls, and concrete for the floor. These combined properties are listed in Table C-3.

The fires used in the CFAST model are based on stacks of wood pallets. This is not meant to suggest that wood pallets are a likely fuel source in the WSBs. Other fuels could be used, but the most important factor in this evaluation is the fire heat release rate, not the specific fuels used to derive the heat release rate. Pallet stacks were chosen as a fuel source because they are well characterized from a fire size and growth standpoint, are moderately severe, and can be easily adjusted by changing the height of the stack (peak heat release rate) and the duration of the peak burning (percentage of fuel consumed). Note that the usage and safety controls associated with the facility make Class A-type combustibles a more likely fire source than flammable liquids. The WSB design incorporates a floor slope for drainage as a safety significant design feature. Spills of combustible liquids in WSBs will drain out of the buildings and then continue to drain away from the buildings via the site slope. Combustible liquids with a hazard greater than 1 per NFPA (Class IIIB combustible liquids) are also administratively prohibited inside WSBs [C-6].

Time-dependent heat release rate curves are used to describe the fire growth, steady burning, and fire decay in the model. This section describes the development of a heat release rate for a single burning pallet stack. Each time a pallet stack ignites in the model, it burns according to the heat release rate for a single burning stack, independent of any stacks already burning. The ignition of subsequent pallet stacks is described in Section 3.

The heat release rate curve for an individual pallet stack has four components: peak heat release rate, growth rate, decay rate, and duration of peak burning. The peak heat release rate of the pallet stack fire is based on a method for wood pallets described by Babrauskas, as presented in the SFPE Handbook, 5th edition [C-18]:

$$\dot{Q} = 919A_p\left(1 + 2.14h_p\right)(1 - 0.03M) \qquad \text{Eq. C-3}$$

where $\dot{Q}$ is the peak heat release rate (kW),

A_p is the area of the pallet (m^2),

h_p is the height of the pallet stack (m), and

M is the moisture content of the wood (%).

The growth rate of the fire up to the peak heat release rate is determined from experimental data presented in the SFPE Handbook, as shown in Figure C-4. A fire that grows as a function of the burning time squared is used to characterize the fire heat release rate growth:

$$\dot{Q} = \alpha t^2 \qquad \text{Eq. C-4}$$

where Q is the heat release rate (kW),

α is a parameter characterizing the fire growth speed (kW/sec^2), and

t is the time (sec).

A t^2-fire with an α value of 0.09 provides a very good approximation of the growth rate of this fire. For reference, this growth rate falls between the growth rates of "ultra-fast" and "fast" t^2-fires commonly used in fire analysis. Figure C-4 also shows the estimation of the peak heat release rate of the fire per the method described above. The peak heat release rate in the figure is based on a pallet stack with dimensions of 1.22 m long, 1.22 m wide, and 1.22 m high, as presented in the SFPE Handbook. A moisture content of 9 percent provides the best match to the data in Figure C-4, so this value is used for all of the modeling.

After a period of steady burning, the fire heat release rate is assumed to decay at the same α value as the growth rate. The duration of steady burning is adjusted so that when the fire completely burns out (i.e., end of the decay period), the desired total mass loss percentage is achieved. The model baseline assumes that 90 percent of the original mass of a pallet stack is consumed in the fire. The experimental heat release rate curve shown in Figure C-4 for a stack of eight 1.22 m x 1.22 m pallets suggests an approximate total mass consumption of between 70 percent and 100 percent (assuming a heat of combustion of 12 MJ/kg, and an individual pallet mass between 19 and 26 kg [42 and 58 lbs]). The fires in this analysis are also expected to burn in under-ventilated conditions, which will lead to incomplete combustion. A total mass loss of 90 percent was chosen as representative of the potential conditions.

An example heat release rate curve for input in the CFAST model is shown in Figure C-5. Pallets with length of 1.22 m (4.0 ft), width of 1.02 m (3.3 ft), height of 15.2 cm (6.0 in), and an estimated mass of 15 kg (33 lbs) are used to develop the heat release rates for the model. An individual heat release rate curve is generated for each pallet stack size considered in the CFAST model.

The model pallet is smaller than those described in Figure C-4 but is used for convenience as this smaller pallet could fit between the waste drum stacks and outer walls as shown in the design drawings (see also Figure C-6 in Section 3). As noted above, the specific characteristics of the pallets are used only as a guide to develop the fire heat release rate, which is the most important fire characteristic. Other fuels could have been used as the basis for fire heat release rates in this analysis.

Table C-3. *Material Properties used in the CFAST Model*

Material	Thickness cm [in]	R-Value m·^{2}K/W [hr·°F·ft^{2}/BTU]	Thermal Conductivity W/m·K [BTU·in/hr·ft^{2}·°F])	Specific Heat[1] kJ/kg·K [BTU/lb·°F]	Density[1] kg/m^{3} [lb/ft^{3}]	Emissivity[1] N/D
Metal Insulated Panels with rigid polyisocyanurate foam core [C-12, C-13, C-19]	6.4 [2.5]	3.3 [19.0]	0.019[2] [0.131]	1.21 [0.29]	43.3 [2.7]	N/A
Mineral Wool Insulation in Walls [C-12, C-20]	8.9 [3.5]	2.3 [13.0]	0.039[2] [0.269]	0.84 [0.20]	64.2 [4.0]	N/A
Mineral Wool Insulation in Ceilings [C-13, C-20]	30.5 [12.0]	6.7 [38.0]	0.046[2] [0.316]	0.84 [0.20]	64.2 [4.0]	N/A
Gypsum wallboard	1.59 [0.62]	N/A	0.26[1] [1.80]	0.90 [0.21]	790. [49.2]	0.9
Concrete	15.4 [6.0]	N/A	0.80[1] [5.55]	0.75 [0.18]	2320. [144.5]	0.9
Steel (columns)	1.55[3] [0.61]	N/A	43.0[1] [298]	0.47 [0.11]	7800 [485.8]	0.8
Wood (in pallet stacks)	1.60[4] [0.63]	N/A	0.16[1] [1.11]	1.26 [0.30]	720. [44.8]	0.9
Composite Wall (CFAST)	16.8 [6.6]	N/A	0.030[1] [0.204]	0.98 [0.24]	125 [7.8]	0.9
Composite Ceiling (CFAST)	32.1 [12.6]	N/A	0.047[1] [0.329]	0.84 [0.20]	100 [6.2]	0.9

Notes: [1] Generic material properties to provide a reasonable approximation.
[2] Thermal conductivity derived from R-Value and thickness (Thermal conductivity = thickness / R-Value).
[3] Based on web thickness of W12x65 steel column.
[4] Assumed thickness of wood pallet planking. A common standard pallet deck board thickness is 5/8 in. (1.6 cm).
N/D = Non-dimensional
N/A = Not Applicable

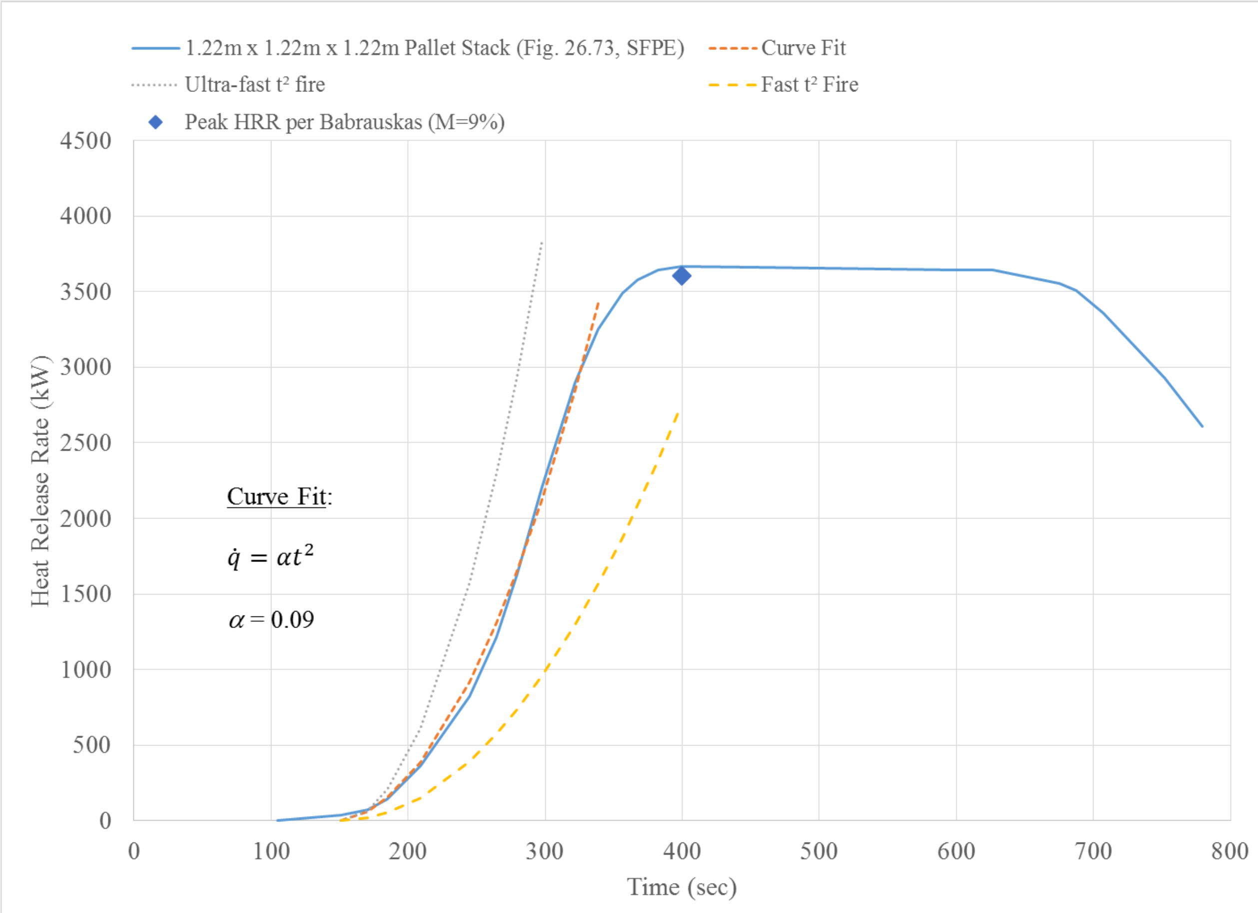


Figure C-4. *Wood pallet heat release rate and curve fits*

The fuel's heat of combustion is used to calculate the mass loss from the heat release rate curve. The heat of combustion is based on the heats of combustion of wood and polyethylene. Some plastic content is assumed because many modern structure fires involve some amount of plastics. Plastic is considered in the model to provide a conservative approximation of a denser, sootier smoke. A plastic content of 10 percent by mass is assumed for the fuel. The primary impacts of using plastics as a part of the modeled fuel packages are increased heat of combustion and increased soot and carbon monoxide in the combustion products. The heats of combustion for wood and polyethylene are combined according to their mass ratio in the fuel:

- Wood (90 percent of stack mass): 17.1 kJ/g (7350 BTU/lb)
- Polyethylene (10 percent of stack mass): 43.6 kJ/g (18700 BTU/lb)
- Combined: 20.0 kJ/g (8540 BTU/lb)

Table C-4 shows the peak heat release rate and mass for pallet stacks of varying height. The development of other combustion chemistry inputs is discussed below.

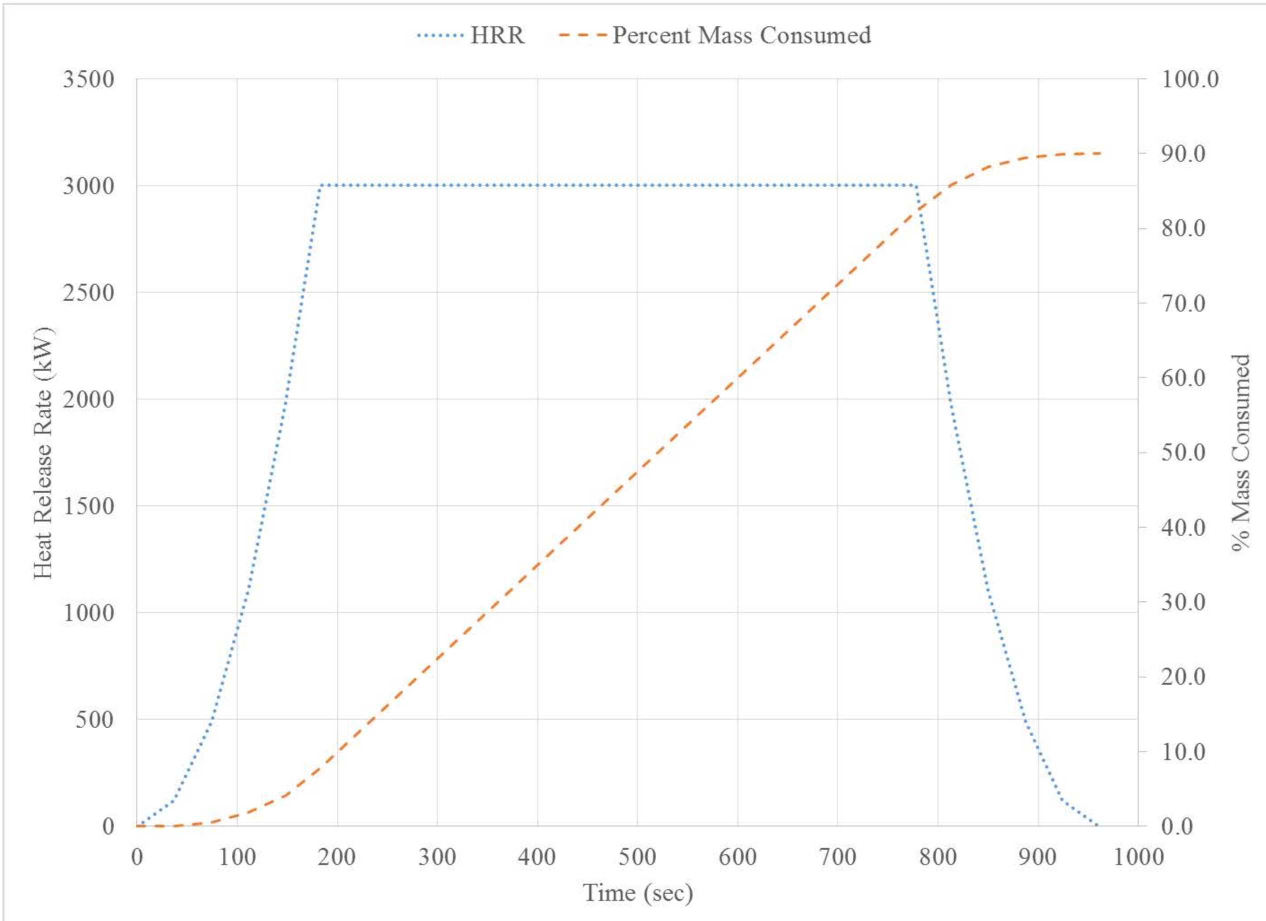


Figure C-5. *Example heat release rate curve for an 8-pallet stack (1.22 m x 1.02 m [4.0 ft x 3.7 ft])*

In addition to the heat release rate curve and heat of combustion, the CFAST model requires the user to input the chemical structure of the fuel and the yields of soot and carbon monoxide (CO) from combustion of the fuel.

Table C-4. *Pallet Stack Peak Heat Release Rates and Masses*

Number of Pallets in Stack	**Peak Heat Release Rate** (kW [BTU/sec])	**Stack Mass** (kg [lbs])
5	2190 [2070]	75 [165]
6	2460 [2330]	90 [198]
7	2730 [2590]	105 [231]
8	3000 [2840]	120 [264]
10	3540 [3360]	150 [330]

There is no specific chemical formula for wood. However, the basic ratio of C-H-O by mass in typical woods is approximately 50 percent C, 6 percent H, and 44 percent O [C-21].

This equates to a chemical formula of approximately $C_7H_{10}O_5$, which has a molar mass of 174.1 g (6.13 oz). Polyethylene is characterized as $(C_2H_4)_n$, which has a molar mass of 28.1 g (0.99 oz). In order to achieve a 10 percent mass of plastic in the total mass, the ratio of moles of wood to moles of plastic in the fuel must be 1:0.69. Summing the number of C, H, and O atoms derived from these ratios results in the chemical formula used for input into CFAST: $C_{8.38}H_{12.76}O_5$.

The yields of soot and carbon monoxide from the burning fuel are based on the yields of these products in well-ventilated combustion conditions. The well-ventilated yields are then adjusted using an equivalence ratio of 1 to provide a measure of correction for under-ventilated conditions that develop during the fire [C-22]. The yields of the products are considered separately for each of the component fuels (wood and polyethylene), then combined based on their mass ratio. The yields are shown in Table C-5.

The adjustment of product of combustion yields with an equivalence ratio is based on a method outlined in the SFPE Handbook, 5th edition [C-22]. Equation 36.74 is used to adjust the yields:

$$fp = fp_\infty \left\{ 1 + \frac{\alpha}{\exp\left[\left(\frac{\Phi}{\beta} \right)^{-\xi} \right]} \right\} \qquad \textbf{Eq. C-5}$$

where fp is the fire product yield (kg produced/kg fuel consumed),

fp_∞ is the fire product yield under well-ventilated conditions (kg produced/kg fuel consumed),

Φ is the equivalence ratio (non-dimensional), and

α, β, ξ are correlation coefficients for each fuel (non-dimensional).

The correlation coefficients for the above equation are identified in Table 36.12 of the SFPE Handbook, which is adapted in Table G-6.

Table C-5. *Soot and Carbon Monoxide Yields*

Combustion Product	**Combustion Product Yield** (g/g fuel burned)				
	Well-Ventilated Conditions		**Equivalence Ratio = 1**		**Combined Yield, based on mass ratio**[1]
	Wood	Polyethylene	Wood	Polyethylene	
Soot	0.015	0.060	0.018	0.070	0.023
Carbon Monoxide	0.004	0.024	0.018	0.074	0.024

[1] These are the values used in the CFAST model.

Table C-6. *Correlation coefficients to account for the effects of ventilation on the generation rates of CO, hydrocarbons, and soot*[1]

Material	CO			Hydrocarbons			Soot		
	α	b	x	α	b	x	α	b	x
PE[2]	26	1.39	2.8	220	1.90	2.5	2.2	2.50	1.0
Wood	44	1.30	3.5	200	2.33	1.9	2.5	2.15	1.2

[1] Adapted from Table 36.12 in the SFPE Handbook, 5th ed. [C-22]
[2] PE = Polyethylene

Fire Modeling Assumptions

The following assumptions are made in developing the fire model:

1. Given the location of TWF, ambient conditions are considered to be 20 °C (68 °F), 77600 Pa (0.766 atm), and 50 percent relative humidity.
2. The lower oxygen limit for combustion is assumed to be 10 percent.
3. The electrical closet and fire riser room are not included in the model, since these spaces are normally closed. The model accounts for the volume of the fire riser room and electrical closet by deducting the volume of those spaces from the volume of the entire building. This is appropriate given that CFAST is a two zone control volume model.
4. The ceiling height is assumed to be an average height, since the actual floor and ceiling have slight slopes. This is appropriate given that CFAST is a two zone control volume model.
5. Fires can be approximated as stacks of wood pallets with 10 percent plastic content to approximate some plastic in the fuel package.
6. Wood planking on pallets is 1.60 cm (5/8 in) thick, which is a standard thickness.
7. 90 percent of the original mass of each pallet stack is consumed in the fire.
8. Ignition of subsequent pallet stacks occurs when the surface temperature of the wood is ≥ 350 °C (662 °F) and the incident heat flux is ≥ 10 kW/m² (0.88 BTU/sec·ft²) [C-23].
9. The ceiling assembly is assumed to remain intact during at least the first 20 minutes of the fire, based on typical gypsum wall board performance in fire testing.
10. The temperature of the steel column below the ceiling is taken as the maximum temperature on the column web. While the flange closest to the fire may be at a higher temperature, the column will redistribute stress through the cross section based on yield strength and stiffness gradients, which vary with the local temperature across the column. The maximum heat flux to the column web occurs on the edge of the web closest to the center of the fire. Because this location is coincident with a flange,

the flange is assumed to be transparent to all heat transfer, maximizing the heat flux (see Figure C-8 in Section 3).

11. Automatic sprinklers are modeled for understanding likely activation times but do not control the fire. The sprinkler characteristics are taken from the design drawings and specifications [C-9, C-24]:
    - Maximum spacing: 3.2 m x 2.8 m (10.4 ft x 9.1 ft)
    - Maximum distance from fire center: 2.1 m (6.9 ft)
    - Distance below ceiling: 25.4 cm (10.0 in)
    - Activation temperature: 141 °C (286° F)
    - Standard response, RTI = 100 $m^{1/2}sec^{1/2}$ (180 $ft^{1/2}sec^{1/2}$)
12. Manual fire suppression by the fire department is not considered.
13. Flashover conditions in the WSB are assumed to occur when the hot, upper gas layer is ≥ 500 °C (932 °F), the incident heat flux to the center of the floor is ≥ 20 kW/m^2 (0.88 $BTU/sec \cdot ft^2$), or the doorway has established flaming coming out (approximate heat release rate of these flames ≥ 50 kW (47 BTU/sec)) [C-25].
14. Automatic door closers on the personnel doors are considered inoperable. These doors are 1-hour fire protection rated and are equipped with closers. These closers are a credited control and are tested quarterly, per the latest TSR [C-6].

3. Analytical Methods and Computations

Structural Analysis

The software used to analyze the structural performance of a representative portal frame is Intergraph GT STRUDL (version 33), a finite element analysis software package that includes beam, plate, and shell elements. The analysis uses the geometry, dimensions, and section properties of the center frame of a TWF Waste Storage Building. This frame is the most highly stressed section of the building structure, with a tributary width of applied dead load of 4.75 m (15.58 ft). Dead loads are derived directly from the TWF design calculations as shown in Tables G-1 and G-2, as well as the pinned base boundary conditions [C-7]. Out of plane translational restraints are used for stability of the model. The GT STRUDL input files are included in Attachment 3 of EC.FY17.NFDI.LANL.TWF.StructuralFire. The column elements use the properties of steel materials at approximately 700 °C (1290 °F), while the beam elements use room temperature steel properties.

The *self-weight of members* function is used to derive the dead load contribution of the primary steel framing. The load is distributed from the roof decking to the purlins, which then evenly distribute load to the primary structural frames of each building. The purlin loads for this model are determined by point loads representing a 4.75 m (15.58 ft) long line load from Table C-2 that is transferred to the center portal frame, plus the self-weight of the roof purlin W14x22 framing (32.8 kg/m (22.0 lbs/ft) for interior purlins and 44.7 kg/m (30.0 lbs/ft) for W14x30 exterior purlins). Plots of the load distribution are provided in Attachment 1 of

EC.FY17.NFDI.LANL.TWF.StructuralFire. The derivations of interior and exterior purlin loads are shown below:

$$(15ft, 7in) * \left(\frac{120.8lbs}{ft} + \frac{22lbs}{ft}\right) = 2225lbs \quad \textbf{Eq. C-6}$$

$$(15ft, 7in) * \left(\frac{60.4lbs}{ft} + \frac{30lbs}{ft}\right) = 1409lbs \quad \textbf{Eq. C-7}$$

The GT STRUDL *stiffness analysis* command is used to perform a stress analysis, followed by a design check adhering to the American Institute of Steel Constructors 14th Edition Design Manual. As A992 Grade 50 steel properties are not available in GT STRUDL, A572 Grade 50 steel properties are substituted, since these steels have the same design properties. Dead loads are assigned a load factor of unity in line with assumption #2, however the LRFD check for design capacity will incorporate ϕ factors for capacity. Plots of the moment and axial load are generated to confirm assumption #6.

Fire Modeling

The two-zone fire model CFAST (version 7.2.1) is used to evaluate the progression of fires, the fire environmental conditions, and the resulting temperature of steel columns. A fire model is used in this case to capture the contribution of the hot gas layer and heated compartment surfaces to the heating of the steel columns, in addition to the radiant heating from the fire itself. The basic fire model arrangement is shown in Figure C-6. One pallet stack is located adjacent to columns D2, D3, D4, and A3. These locations are chosen because the largest structural stresses are located on the three central portal frames. In particular, columns D3 and A3 are part of the portal frame considered in the structural evaluation. The pallet stack at column D3 is assumed to ignite first in all scenarios. Subsequent ignition of pallet stacks depends on the dynamic fire environment calculated by the model. Figure C-6 also shows the concrete footers and doors included in the model.

Pallet ignition conditions and steel column temperatures are determined in CFAST by using a series of targets. These targets are defined by material properties, thickness, position, and orientation. The model calculates the total incident heat flux and heat loss of a target to determine its surface temperature. Five targets are used to identify the location of peak incident heat flux and temperature on the pallet stacks at columns D2 and D4. Only two targets are necessary for the pallet stack at column A3 because its location is more distant from the other three fires. When any of the targets reach the ignition conditions described in fire modeling assumption 8, the pallet stack ignites in the model. The ignited pallet stack burns with a heat release rate developed as described in Section 2 for the height of the stack. The red arrows in Figure C-7 show the position and orientation of the targets on each pallet stack. The material for each of these targets is wood.

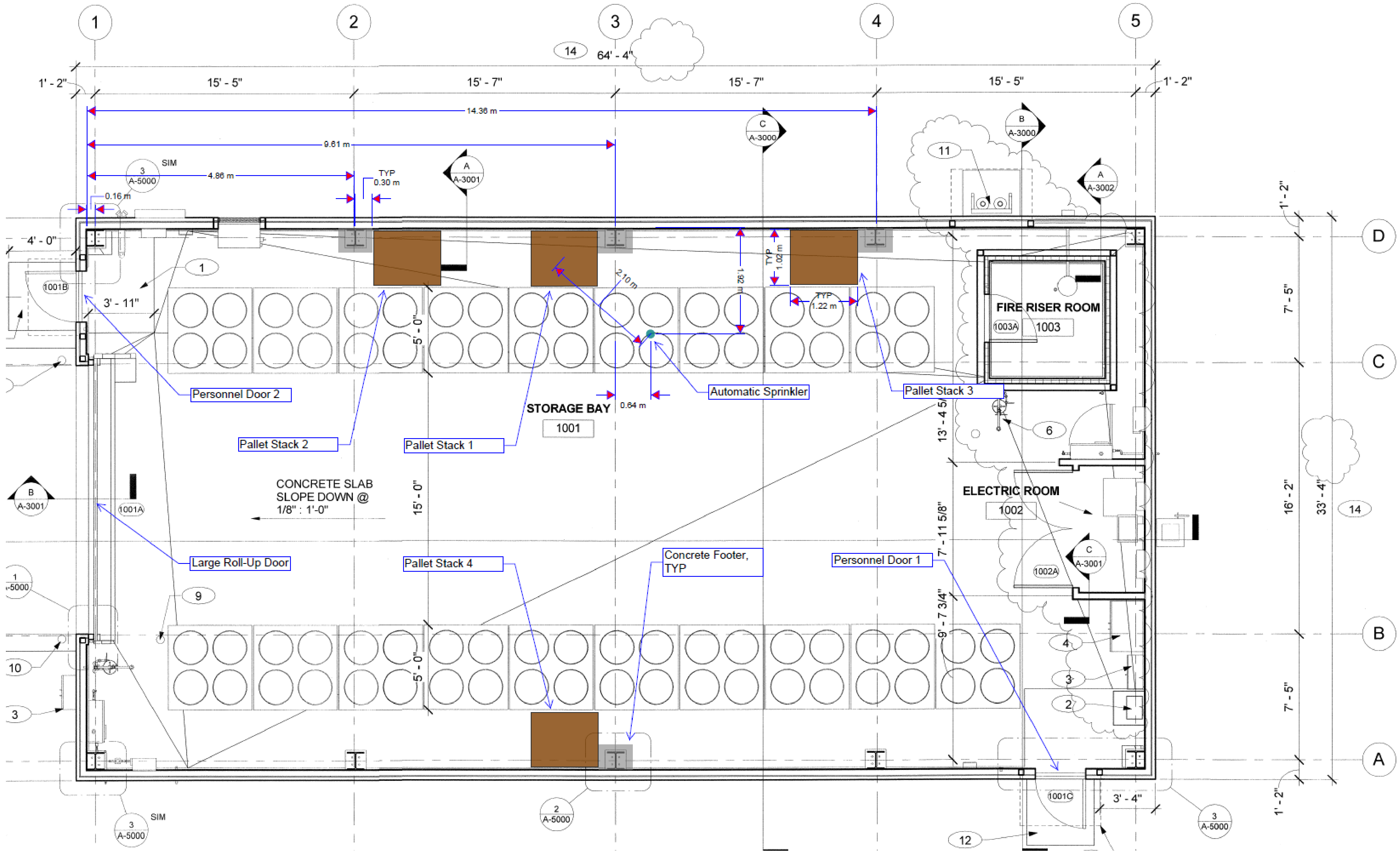


Figure C-6. *General arrangement of fire model*

Thirty-seven targets are used to identify the location of peak incident heat flux and temperature on steel columns D2, D3, D4, and A3. Targets are concentrated on the lower part of the column so that a more precise determination of the peak heat flux may be obtained. In CFAST, the point source of radiation is assumed to be at 1/3 of the flame height, which is coincident with the lower part of the column. Column A1 is remote from all fires, so only seven targets are included over the height of the column. The position of column targets is shown in Figure C-8. The flange closest to the fire is assumed to be transparent to all heat transfer, maximizing the heat flux at the target location. The material for each of these targets is steel.

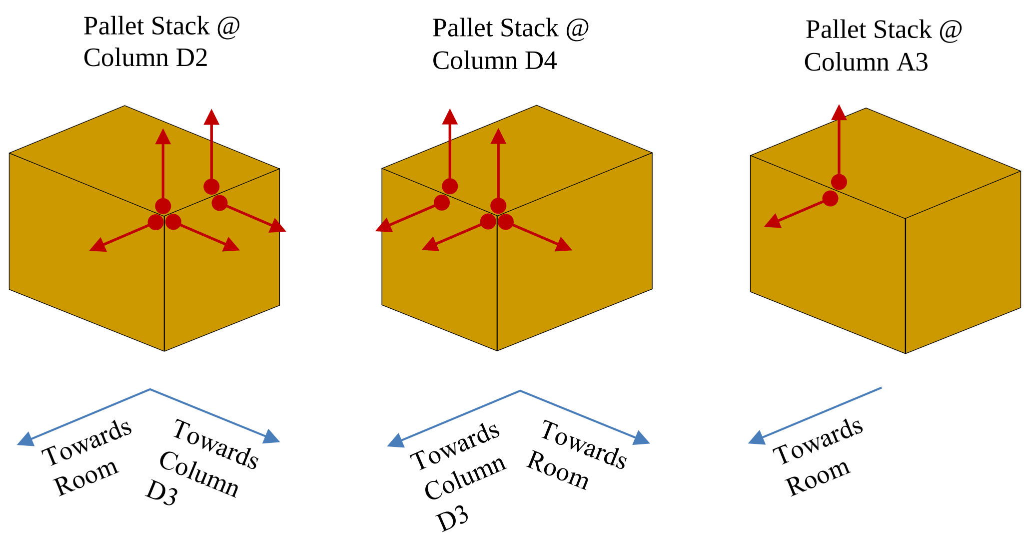
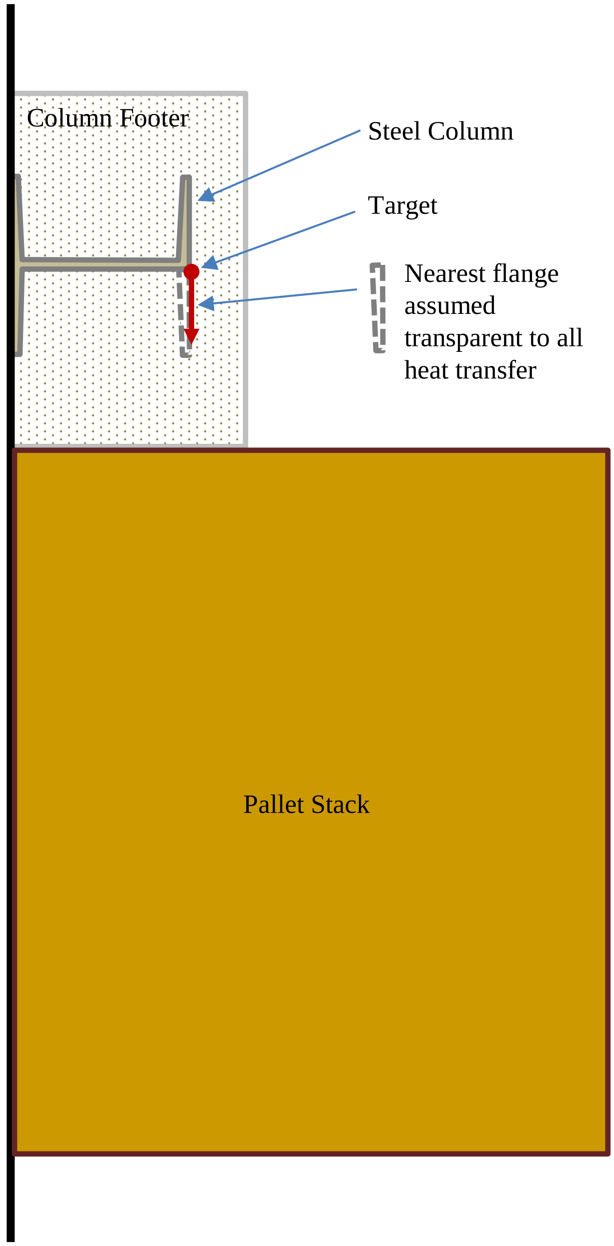


Figure C-7. *Location of CFAST targets for pallet stack ignition determination*



Target Heights

D2,D3,D4,A3	A1
4.07 m (13.4 ft)	4.0 m (13.1 ft)
4.0 m (13.1 ft)	3.5 m (11.5 ft)
3.7 m (12.1 ft)	3.0 m (9.8 ft)
3.4 m (11.2 ft)	2.5 m (8.2 ft)
3.1 m (10.2 ft)	2.0 m (6.6 ft)
2.8 m (9.2 ft)	1.5 m (4.9 ft)
2.5 m (8.2 ft)	1.0 m (3.3 ft)
2.2 m (7.2 ft)	
1.9 m (6.2 ft)	
1.6 m (5.2 ft)	
1.55 m (5.1 ft)	
1.5 m (4.9 ft)	
1.45 m (4.8 ft)	
1.4 m (4.6 ft)	
1.35 m (4.4 ft)	
1.3 m (4.3 ft)	
1.25 m (4.1 ft)	
1.2 m (3.9 ft)	
1.15 m (3.8 ft)	
1.1 m (3.6 ft)	
1.05 m (3.4 ft)	
1.0 m (3.3 ft)	
0.95 m (3.1 ft)	
0.9 m (3.0 ft)	
0.85 m (2.8 ft)	
0.8 m (2.6 ft)	
0.75 m (2.5 ft)	
0.7 m (2.3 ft)	
0.65 m (2.1 ft)	
0.6 m (2.0 ft)	
0.55 m (1.8 ft)	
0.5 m (1.6 ft)	
0.45 m (1.5 ft)	
0.4 m (1.3 ft)	
0.35 m (1.1 ft)	
0.3 m (1.0 ft)	
0 m (0 ft)	

Plan View

Figure C-8. *Location of CFAST targets for column incident heat flux and temperature determination*

CFAST uses a non-adjustable point-source model to calculate radiation heat transfer from fires. This model begins to lose accuracy at small distances, such as those between the pallet stack fires and the columns. Where the ratio of the separation distance (L) to the hydraulic diameter (D_h) of the fire is less than about 2.5, alternate methods should be considered. The separation distance is between the center of each individual pallet stack fire and the column target surface. The hydraulic diameter of this fire is determined from the following equation:

$$D_h = \sqrt{\frac{4A}{\pi}} \qquad \text{Eq. C-8}$$

where D_h is the hydraulic diameter (m), and

A is the plan area of the pallet stack (m^2).

The hydraulic diameter of this fire is 1.24 m (4.07 ft). The separation distance between the center of the pallet stack and the column target location is 0.94 m (3.1 ft). Since the L/D_h ratio is only 0.76, a method other than the CFAST point source should be considered for fire radiation to the columns.

The method developed by Shokri and Beyler [C-26] is one potential method that can be used to determine the radiant heat flux from the pallet stack fires to the columns. This method will provide reasonable results, as it is valid for L/D_h ratios greater than about 0.7. In this method, the flame is assumed to be a cylindrical blackbody radiator with an average emissive power. The incident radiative heat flux to a target outside of the flame is given by:

$$\dot{q}'' = f_s E F \qquad \text{Eq. C-9}$$

where E is the average emissive power of the fire (kW/m^2),

F is the view factor between the target and the flame (non-dimensional), and

f_s is a safety factor.

The discussion of the Shokri and Beyler method [C-26] suggests using a safety factor of two, which is used in the present analysis.

The fire emissive power is a function of the hydraulic diameter of the flame:

$$E = 58(10^{-0.00823 D_h}) \qquad \text{Eq. C-10}$$

The view factor in the Shokri and Beyler method is based on the flame height, diameter of the fire, and distance between the target and the flame center as shown in Figure C-9. The equation for this the view factor is

$$F_{dA1-2} = \frac{1}{\pi S} tan^{-1}\left(\frac{H}{\sqrt{S^2-1}}\right) - \frac{H}{\pi S} tan^{-1}\sqrt{\frac{S-1}{S+1}} + \frac{AH}{\pi S\sqrt{A^2-1}} tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}}$$ **Eq. C-11**

where, $S = L/(D_h/2)$,

$H = H_f/(D_h/2)$, and

$A = (H^2+S^2+1)/(2S)$.

The flame height is based on the following relation:

$$H_f = 0.23\dot{Q}^{2/5} - 1.02D_h$$ **Eq. C-12**

where H_f is the flame height (m), $\dot{Q}$ is the fire heat release rate (kW), and

D_h is the hydraulic diameter of the fire (m).

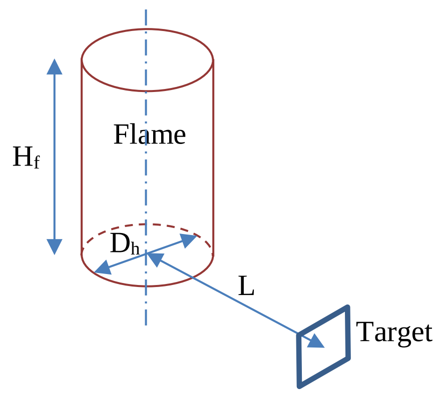


Figure C-9. *Cylindrical flame view factor geometry used in the Shokri and Beyler method*

The view factor from the Shokri and Beyler method does not match the geometry of this analysis as shown in Figure C-10. Because the center of the flame is offset from the column web, the plane of the target does not match the plane of the web. Therefore, an alternate view factor is substituted to apply the correct geometry to the analysis. The geometry of the alternate view factor is shown in Figure C-11. This view factor allows an offset from the representative flame cylinder, while maintaining the target in the same plane as the column web.

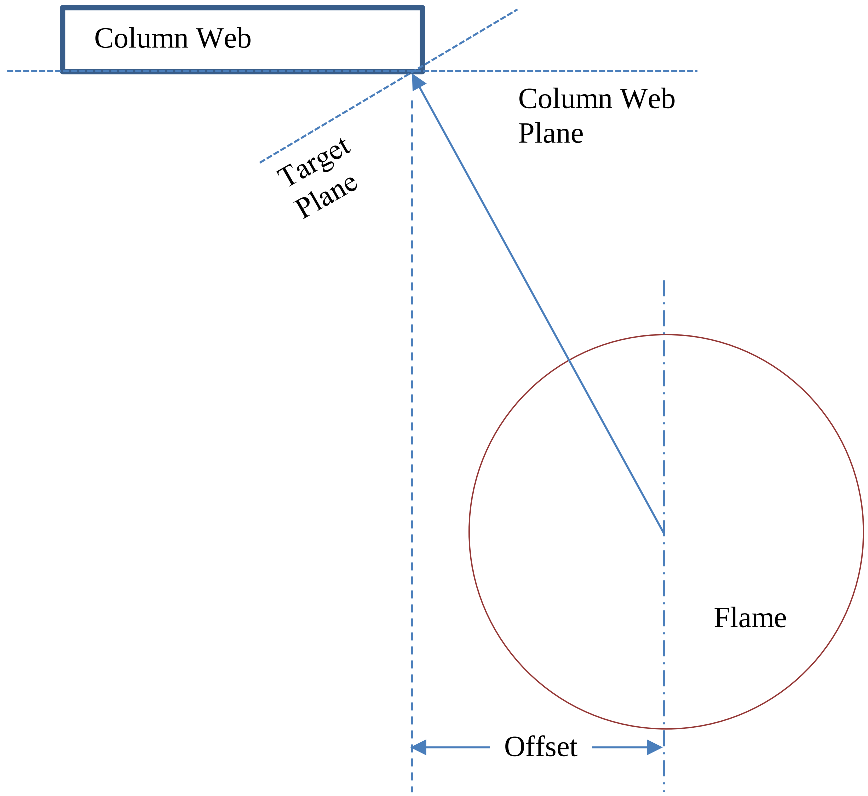


Figure C-10. *Geometry between flame and column web using the Shokri and Beyler view factor*

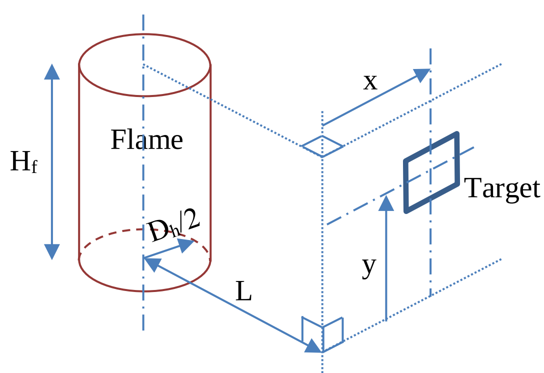


Figure C-11. *Alternate cylindrical flame view factor geometry*

The equation for the view factor shown in Figure C-11 is:

$$F = \frac{S}{B} - \frac{S}{2B\pi}\left\{\cos^{-1}\left(\frac{Y^2 - B + 1}{A - 1}\right) + \cos^{-1}\left(\frac{C - B + 1}{C + B - 1}\right) - Y\left[\frac{A + 1}{\sqrt{(A-1)^2 + 4Y^2}}\cos^{-1}\left(\frac{Y^2 - B + 1}{B^{\frac{1}{2}}(A-1)}\right)\right] - C^{\frac{1}{2}}\left[\frac{C + B + 1}{\sqrt{(C + B - 1)^2 + 4C}}\cos^{-1}\left(\frac{C - B + 1}{B^{\frac{1}{2}}(C + B - 1)}\right)\right] + H\cos^{-1}\left(\frac{1}{B^{\frac{1}{2}}}\right)\right\} \qquad \text{Eq. C-13}$$

where $S = L / (D_h /2)$,

$X = x / (D_h /2)$,

$Y = y / (D_h /2)$,

$H = H_f /(D_h /2)$,

$A = X^2+Y^2+S^2$,

$B = S^2+X^2$, and

$C = (H-Y)^2$.

A Microsoft Excel spreadsheet is used to calculate the heat flux from the Shokri and Beyler method, and is included in Attachment 4 of EC.FY17.NFDI.LANL.TWF.StructuralFire.

Several initial scoping CFAST models were developed to determine if the peak heat flux to the columns as calculated by CFAST was consistent with the peak flux obtained using the Shokri and Beyler method. If the peak heat fluxes are inconsistent, the thermal response of the CFAST targets used to determine the peak column temperature would be inappropriate. Using the arrangement depicted in Figure C-6 above, the initial scoping CFAST models were run with one pallet stack fire (of varying height), very high ceilings, and a very large vent in order to determine the peak heat flux to the column[1]. The peak heat flux calculated from the Shokri and Beyler methods is approximately 74 kW/m^2 (6.5 BTU/sec·ft^2) for all the pallet stack heights considered, due to the proximity between the pallet stacks and columns. The initial scoping CFAST models resulted in peak heat fluxes to the columns inconsistent with those calculated with the Shokri and Beyler method, which would result in inaccurate prediction of peak column temperatures.

[1] Running the model with this arrangement minimizes the heat flux contribution of the hot gas layer and compartment boundaries to the column. The Shokri and Beyler method is based on fires burning outside, so this method provides a good point for comparison.

Additional scoping CFAST models were developed to adjust the peak flux to the columns such that it matched the peak heat flux from the Shokri and Beyler method. The position of the fire was adjusted iteratively in the additional scoping CFAST models until the peak heat flux on the column obtained in CFAST matched that of the Shokri and Beyler method. This adjusted position of the pallet stacks is used in the main CFAST models, with the adjustment being unique for each stack size (each stack size has a different peak heat release rate). The positions of the CFAST pallet stack targets are also adjusted so that the modeled distance between the pallet stacks remains constant as shown in Figure C-6. This ensures that the ignition times of the other pallets are not impacted by shifting the fire positions.

This scoping work allows the steel column target temperatures generated by the various CFAST models to be directly used without further analysis. The alternative is to adjust each column temperature output of each CFAST model run to account for the offset fire location, which is a more time consuming effort.

The main CFAST model is executed using the adjusted fire positions, varying the pallet stack size, number of pallet stacks, and ventilation arrangement. These varying conditions are used to determine the smallest fire size that creates conditions where structural collapse could be possible. The input files for the main and scoping CFAST models are included in Attachment 5 of EC.FY17.NFDI.LANL.TWF.StructuralFire.

4. Results

Structural Evaluation

The results of the GT STRUDL analysis are that the fire-weakened column sections are under the most stress at the moment frame joints where the top of the columns attach to the roof beams. Based on the LRFD code equations for Grade 50 steel, the nominal D/C ratios for a dead load case are 0.06 as shown in Table C-7. This is lower than the ratio of yield stress of structural steels at 700 °C (1290 °F), which have been conservatively assumed to be approximately 0.1. In essence, the WSB structural columns should have a margin of safety of 40-70 percent, even when heated to 700 °C (1290 °F). The vertical roof deflection is 0.28 inches, which is small for a 31 foot, 8 inch wide span, confirming assumption #6. For serviceability, a small deflection for a roof structure is considered to be L/360, where L is the span length, or approximately one inch for the TWF building structure. Where steel temperatures do not exceed 700 °C (1290 °F), the structure will not become overstressed. Overstressing of the columns will begin at some temperature above 700 °C (1290 °F). However, the precise temperature and structural margin at higher temperatures is unknown due to the lack of steel strength and stiffness property data above 700 °C (1290 °F).

Table C-7. *LRLD Code Check Results for TWF columns*

Member Number	Section Size	KL/r	Nominal D/C
1,2	W12x65	0.068	0.018
7,10	W12x65	0.068	0.032
8,11	W12x65	0.068	0.047
9,12	W12x65	0.068	0.061

Fire Modeling

The set of CFAST fire model scenarios evaluated is shown in Table C-8. In addition to varying the ventilation and fire heat release rate through pallet stack variation, some additional scenarios vary the duration of peak burning, standoff distance from the column, and impact of automatic sprinklers. The results of the CFAST models are presented in Table C-9 and Figures G-12 and G-13, with the table presenting some key outputs and the figures presenting the maximum column temperatures.

The CFAST models considered in this evaluation all result in substantial fires, as shown in Table C-9. Peak heat release rates of the fire inside the WSB storage room range from about 2,000 kW (1,900 BTU/sec) to 14,000 kW (13,270 BTU/sec), with at least two pallet stacks burning in most scenarios. The resulting upper layer temperatures range from 338 °C (640 °F) to 826 °C (1,518 °F). Many of these temperatures are indicative of flashover conditions, which occur in several scenarios.[2] Flashover conditions generally do not occur where the pallet stack size is less than five pallets high or when the large roll-up door is open.

Peak heat fluxes to the columns are greater than the 74 kW/m^2 (6.5 BTU/sec·ft^2) direct radiation calculated by the Shokri and Beyler method in several cases, indicating a significant contribution from the hot gas layer and room surfaces. However, in some cases peak heat fluxes are less than the expected 74 kW/m^2 (6.5 BTU/sec·ft^2). This occurs because the pallet stacks that ignite later are unable to burn at their prescribed peak heat release rates (due to lack of ventilation), and the sooty, hot gas layer between the fire and the column attenuates the fire radiation reaching the column.

Figure C-12 shows the maximum column temperatures reached under the varying ventilation conditions considered in this evaluation. As seen in the figure, only scenarios with two personnel doors open consistently result in column temperatures well above 700 °C (1290 °F), and then only with six-high pallet stacks or more. The only scenarios where the maximum temperature of column A1 is above 700 °C (1290 °F) are the six-, seven-, and eight-pallet stack scenarios with two personnel doors open. This is the only column considered in the model that does not have an adjacent pallet stack fire, and is the column most remote from the fires. When the combustible load with two doors open is reduced to five-pallet stacks, only the initial pallet stacks burns and the maximum column temperatures at those stacks only get to about 550 °C (1,022 °F).

All four pallets ignite during the seven- and eight-pallet stack scenarios with one personnel door open. However, the available ventilation limits the inside fire size to about 4,700 kW (4,450 BTU/sec), and columns only reach about 600 °C (1,110 °F). For comparison, Table C-4 shows that the peak open-burning heat release rates of four pallet stacks would be 10,900 kW (10,400 BTU/sec) for seven pallet-high stacks and 12,000 kW (11,400 BTU/sec) for eight pallet-high stacks.

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[2] CFAST is normally used for determining fire compartment conditions up to flashover. Zone models such as CFAST tend to over predict compartment temperatures in a post-flashover fire environment. Since this evaluation is determining the smallest fire size of concern, over-prediction of the temperatures will conservatively bound the smallest fire size.

Significant heat is lost through the open door during scenarios considering the large roll-up door open. As shown in Table C-9, the peak upper layer temperature in seven and eight-pallet stack scenarios is between 380 °C (716 °F) and 495 °C (923 °F), while for other ventilation scenarios, the peak is higher (615 °C (1,139 °F) to 825 °C (1,517 °F)). Insufficient heat is generated in the scenario with the large door open and seven-high pallet stacks to ignite the third and fourth pallets. All four pallets ignite only when the stack size is increased to 8 pallets each with the large roll-up door open. Even in this scenario, the peak upper layer temperature is 495 °C (923 °F), and maximum columns temperatures are about 680 °C (1256 °F) as shown in Figure C-12. Increasing the pallet stack size to 10 pallets per stack with the large roll-up door open results in column temperatures above 700 °C (1290 °F).

Figure C-13 shows the results of scenario variation with two personnel doors open. The four pallet stack scenarios with five-, six-, seven-, and eight-pallets each are repeated for clarity in this figure. One additional scenario considers only three stacks of seven pallets each, where the pallet stack at column D4 is not included. In this scenario the other two pallet stacks still ignite, but the column temperatures are significantly lower than when four stacks are included. Excluding column D4, the average reduction in column temperature with three stacks is 18 percent. In the three-stack scenario, only two columns are above 700 °C (1290 °F).

A second scenario variation considers moving the pallets 0.3 m (1.0 ft) away from the columns. This change lowers the intensity of radiation received at the column from the fire. Moving the fires at columns D4 and A3 reduces the peak column temperature by about two percent.

In ventilation-limited conditions, the completeness of combustion and overall mass loss will be reduced. Another scenario variation considers this reduction. Changing the maximum mass loss of each pallet stack from 90 percent to 75 percent reduces the peak column temperatures by about 6 percent.

Table C-8. *CFAST Fire Scenarios*

Name	Fire	Ventilation	Fire Position	Total Mass Burned	Notes
WSB0149_4x8pallets_ 2doors_90pct	8-pallet stacks, 4 stacks	2 personnel doors open	Against column footer	90%	None.
WSB0149_4x7pallets_ 2doors_90pct	7-pallet stacks, 4 stacks	2 personnel doors open	Against column footer	90%	None.
WSB0149_4x6pallets_ 2doors_90pct	6-pallet stacks, 4 stacks	2 personnel doors open	Against column footer	90%	None.
WSB0149_3x7pallets_ 2doors_90pct	7-pallet stacks, 3 stacks	2 personnel doors open	Against column footer	90%	None.
WSB0149_4x7pallets_ 1door_90pct	7-pallet stacks, 4 stacks	1 personnel door open	Against column footer	90%	None.
WSB0149_4x7pallets_ bigdoor_90pct	7-pallet stacks, 4 stacks	Large roll-up door open	Against column footer	90%	None.
WSB0149_4x8pallets_ 1door_90pct	8-pallet stacks, 4 stacks	1 personnel door open	Against column footer	90%	None.
WSB0149_4x8pallets_ bigdoor_90pct	8-pallet stacks, 4 stacks	Large roll-up door open	Against column footer	90%	None.
WSB0149_4x10pallets _bigdoor_90pct	10-pallet stacks, 4 stacks	Large roll-up door open	Against column footer	90%	None.
WSB0149_4x7pallets_ 2doors_75pct	7-pallet stacks, 4 stacks	2 personnel doors open	Against column footer	75%	None.
WSB0149_4x7pallets_ 2doors_90pct_shift	7-pallet stacks, 4 stacks	2 personnel doors open	2 Pallets shifted away from columns	90%	Pallets at columns D4 and A3 were shifted 0.3 m further from the column.
WSB0149_4x8pallets_ 2doors_90pct_sprink	8-pallet stacks, 4 stacks	2 personnel doors open	Against column footer	90%	Representative of any stack arrangement considered, since activation occurs during growth phase of 1st pallet burning. Heat release rate was held constant at sprinkler activation.

Scoping Model Runs	
WSB0149_5 pallet_base_dist.in	5-pallet fire, original separation distance between column and fire
WSB0149_5 pallet_adj_dist.in	5-pallet fire, adjusted separation distance between column and fire
WSB0149_6 pallet_base_dist.in	6-pallet fire, original separation distance between column and fire
WSB0149_6 pallet_adj_dist.in	6-pallet fire, adjusted separation distance between column and fire
WSB0149_7 pallet_base_dist.in	7-pallet fire, original separation distance between column and fire
WSB0149_7 pallet_adj_dist.in	7-pallet fire, adjusted separation distance between column and fire
WSB0149_8 pallet_base_dist.in	8-pallet fire, original separation distance between column and fire
WSB0149_8 pallet_adj_dist.in	8-pallet fire, adjusted separation distance between column and fire
WSB0149_10 pallet_base_dist.in	10-pallet fire, original separation distance between column and fire
WSB0149_10 pallet_adj_dist.in	10-pallet fire, adjusted separation distance between column and fire

Table C-9. *CFAST Results*

Name	**Pallet Ignition Times** [1,2,3] (seconds)			**Peak Heat Release Rate** (kW [BTU/sec])	**Peak Heat Flux to Columns** (kW/m^2 [BTU/sec·ft^2])					**Peak Upper Layer Temperature** (°C [°F])	**Onset of Flashover conditions**[3,4] (seconds)		
	D2	D4	A3		D2	D3	D4	A1	A3		UL Temp	Floor Heat Flux	Vent Fire
WSB0149_4x8pallets_2doors_90pct	339	466	472	8,680 [8,222]	94.6 [8.3]	69.1 [6.1]	97.3 [8.6]	66.7 [5.9]	94.9 [8.4]	826 [1,518]	500	510	550
WSB0149_4x7pallets_2doors_90pct	397	530	536	8,560 [8,117]	94.5 [8.3]	68.7 [6.1]	95.3 [8.4]	62.5 [5.5]	92.8 [8.2]	807 [1,485]	570	580	630
WSB0149_4x6pallets_2doors_90pct	617	749	757	7,370 [6,989]	88.0 [7.8]	69.1 [6.1]	88.3 [7.8]	52.2 [4.6]	85.9 [7.6]	758 [1397]	870	890	N/A
WSB0149_4x5pallets_2doors_90pct	DNI	DNI	DNI	2,190 [2,072]	10.7 [0.9]	69.5 [6.1]	9.9 [0.9]	8.6 [0.8]	8.9 [0.8]	338 [640]	N/A	N/A	N/A
WSB0149_3x7pallets_2doors_90pct	397	N/A	536	8,150 [7,723]	77.8 [6.8]	73.4 [6.5]	44.0 [3.9]	43.1 [3.8]	76.3 [6.7]	690 [1,273]	570	580	N/A
WSB0149_4x7pallets_1door_90pct	347	455	462	4,690 [4,444]	46.2 [4.1]	68.8 [6.1]	48.7 [4.3]	29.7 [2.6]	48.0 [4.2]	615 [1,139]	570	590	480
WSB0149_4x7pallets_bigdoor_90pct	460	DNI	DNI	5,460 [5,173]	80.1 [7.1]	76.2 [6.7]	12.8 [1.1]	11.3 [1.0]	11.8 [1.0]	380 [719]	N/A	N/A	N/A
WSB0149_4x8pallets_1door_90pct	305	408	415	4,710 [4,463]	44.6 [3.9]	68.2 [6.0]	46.7 [4.1]	30.5 [2.7]	46.0 [4.1]	621 [1,150]	520	540	430
WSB0149_4x8pallets_bigdoor_90pct	361	734	974	8,490 [8,045]	81.3 [7.2]	78.0 [6.9]	81.0 [7.1]	18.1 [1.6]	83.5 [7.4]	495 [923]	N/A	N/A	N/A
WSB0149_4x10pallets_bigdoor_90pct	269	522	598	14,170 [13,432]	91.5 [8.1]	86.1 [7.6]	92.6 [8.2]	38.9 [3.4]	92.7 [8.2]	672 [1,241]	670	690	N/A
WSB0149_4x7pallets_2doors_75pct	397	530	536	8,100 [7,678]	88.0 [7.7]	68.7 [6.1]	88.6 [7.8]	55.9 [4.9]	86.2 [7.6]	775 [1,427]	570	580	630
WSB0149_4x7pallets_2doors_90pct_shift	397	528	536	8,560 [8,104]	94.6 [8.3]	68.7 [6.1]	75.0 [6.6]	62.6 [5.5]	72.5 [6.4]	807 [1,485]	570	580	630
WSB0149_4x8pallets_2doors_90pct_sprink	N/A	N/A	N/A	1,600 [1,517]	7.1 [0.6]	40.4 [3.6]	6.6 [0.6]	5.8 [0.5]	6.1 [0.5]	283 [541]	N/A	N/A	N/A

[1] Pallets are located at the indicated columns. The pallet at column D3 always ignites at time = 0 seconds.
[2] DNI = Did Not Ignite
[3] N/A = Not Applicable
[4] Flashover is defined as an upper layer temperature >500 °C, heat flux to the center of the floor >20 kW/m^2, or sustained burning from a vent (>50 kW).

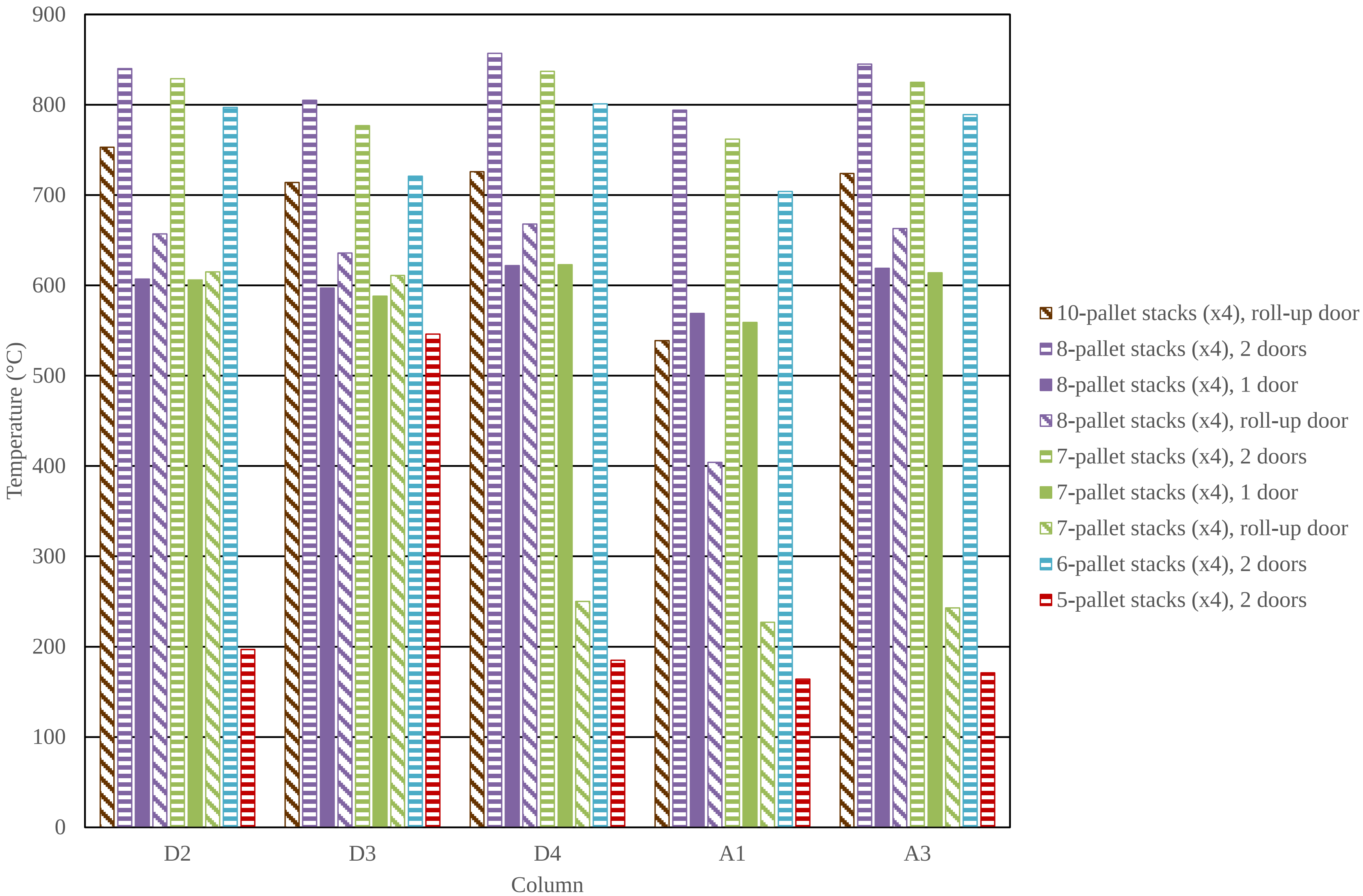

Figure C-12. *CFAST Results - Maximum column temperatures with varying fire ventilation*

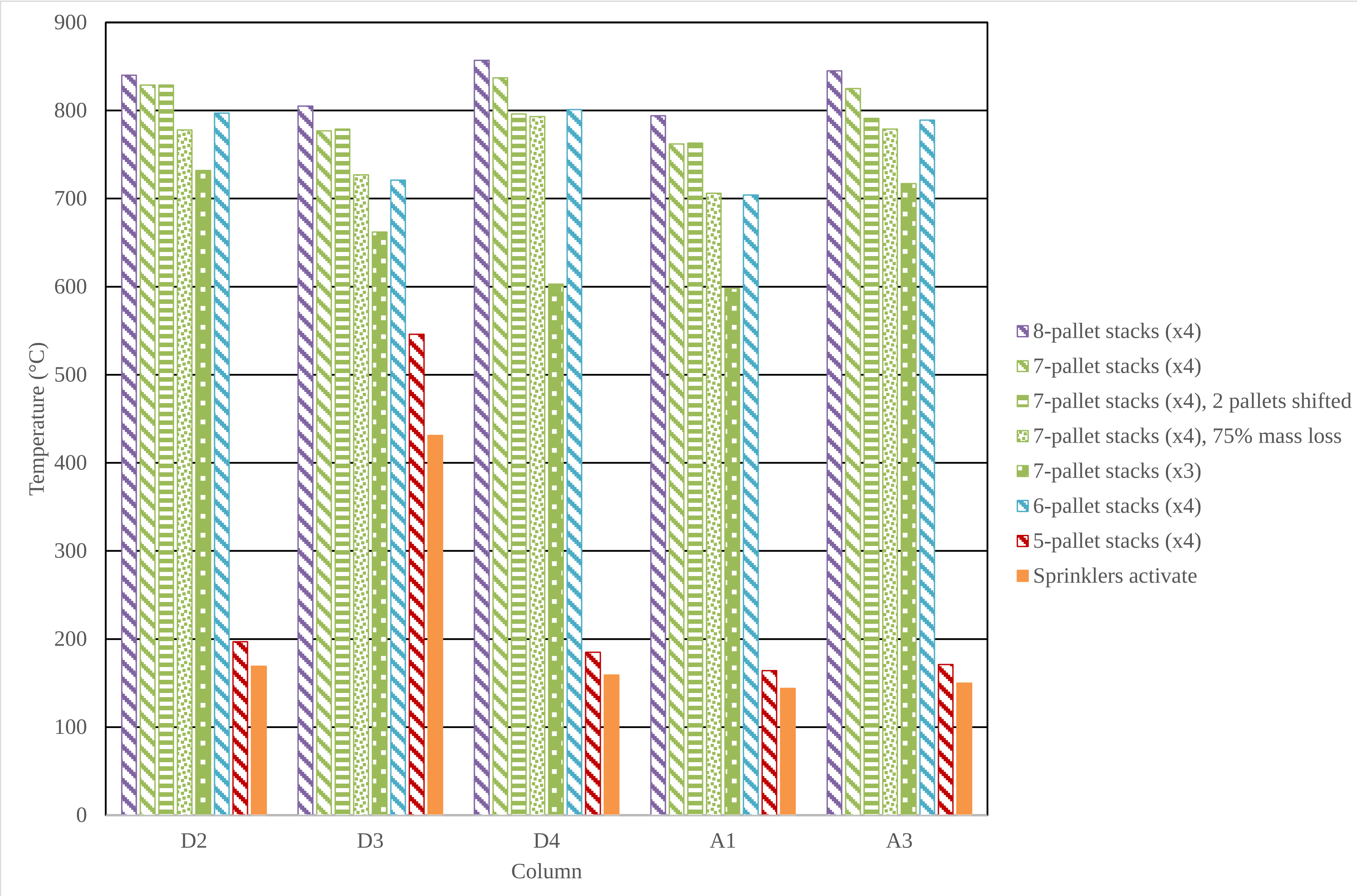

Figure C-13. *CFAST Results - Maximum column temperatures with two personnel doors open*

The last scenario considers the activation of automatic sprinklers. This scenario holds the fire heat release rate steady after the activation of sprinklers. Automatic sprinklers activate in approximately 2.2 minutes, at a fire heat release rate of 1,600 kW (1,517 BTU/sec). Because sprinkler activation occurs during the fire growth phase of the first pallet stack ignited, this scenario is representative of any of the other pallet and ventilation configurations considered. None of the subsequent pallet stacks ignite. The maximum column temperature in this scenario is limited to a single column at 430 °C (806 °F).

Discussion

A summary of the key results of this evaluation are:

1. *Structural columns in the WSBs are lightly loaded and will not fail at temperatures less than 700 °C (1,290 °F).* The actual failure temperature for WSB columns is indeterminate because significant margin exists at 700 °C (1,290 °F), but definitive steel property data above this temperature is unavailable.
2. *Structural collapse due to fire is possible, but only in certain circumstances.* Ventilation must be greater than one open personnel door, and a significant amount of combustibles must be present. If the large roll-up door is open, an even greater amount of combustibles would be required. In the scenarios considering open personnel doors, the credited door closers are also assumed to fail or the doors blocked open.
3. *Flashover conditions are required to drive column temperatures above 700 °C (1,290 °F) but do not always result in column temperatures that high.* Comparing the scenarios that produce flashover conditions in Table C-9 with the maximum column temperatures shown in Figure C-12 indicates that flashover conditions are necessary to drive column temperatures above 700 °C (1290 °F). However, the figure also shows that flashover conditions do not always produce this result. Sufficient ventilation must also be present to allow larger fire sizes.

Given these results, the following judgments on the adequacy of the current safety basis may be made:

1. *The indoor combustible loading specific administrative control must fail to allow for structural collapse.* The most recent Technical Safety Requirements (TSR) document limits the total mass of transient combustibles to 15.9 kg (35 lbs) in a WSB [C-6]. Per this calculation, the minimum amount of transient combustibles needed to cause potential structural collapse is equivalent to four stacks of pallets with six pallets in each stack. This represents 360 kg (792 lbs), which is approximately 22 times more than the TSR limit. Though unlikely to occur while this control is in place and effective, gradual buildup of combustibles to 360 kg (792 lbs) is not unreasonable in a warehouse environment without the control.

2. *The safety significant fire suppression system must fail to allow for structural collapse.* As noted in the Results section, when operable, the fire suppression system would keep the column temperature below 700 °C (1290 °F) and limit the exposure to a single column.

3. *A future change in the safety posture of TWF could result in a potential exposure to the public or co-located worker*. If either of the above controls are eliminated or downgraded, the risk of structural collapse from fire increases. Since the documented safety functions of these controls do not include prevention of structural collapse as a result of fire, the additional risk may be overlooked.

5. Conclusions

Based on the calculation results and safety basis discussion, the authors conclude that the existing control set can adequately prevent this accident. However, prevention of structural collapse from fire should be added to the functional requirements of the existing facility control set to ensure this hazard is properly characterized in the TWF safety basis.

6. References

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