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Ensuring Conservatism/Lessons Learned in Leak Path Factor Calculations with MELCOR

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Abstract

This paper consists of two parts. The first part discusses the steps taken to ensure that leak path factors (LPFs) calculated using the MELCOR computer code for the Los Alamos National Laboratory (LANL) Plutonium Facility Documented Safety Analysis (DSA) are conservative. The second part consists of a statistical analysis of the results from the large number of MELCOR runs performed, and highlights lessons learned.

Accident analyses, including LPF calculations, are a key part of the safety-basis process for nuclear facilities. Ensuring that LPF calculations performed using MELCOR are conservative is a key part of the process. This paper shows the approach used to demonstrate conservatism for an extensive set of MELCOR LPF calculations. Accident analyses are also important in that a great deal can be learned about the performance of systems and the interactions between them. This is demonstrated in the second part of this paper, where lessons learned from a statistical analysis are presented.

When performing LPF calculations, it is necessary to understand the limitations of the physics and numerics built into the code and how modeling (input file) decisions and boundary conditions affect the outcome of an accident simulation. It is also useful to step through a postulated accident scenario from the initial release of material to the room, through the release from the room into surrounding areas of the facility, and finally from the facility to the environment. This process has been performed for several fire scenarios. A significant limitation of MELCOR is that fluid and aerosol transport modeling is one-dimensional. Understanding whether a one-dimensional representation of three-dimensional phenomena such as fire-induced flows is adequate is crucial for producing conservative results. Code-to-code comparisons have been made using National Institute of Standards and Technology (NIST) fire codes to develop this necessary understanding, and where needed to guide MELCOR modeling decisions to ensure conservative results.

When doing a large number of calculations with a large number of parameters, much can be learned about the facility, its associated systems, and their interactions. A statistical analysis was used to show the relative importance of these parameters.

The LPF calculations have been performed for a number of accident scenarios and incorporated into the LANL Plutonium Facility DSA. This paper outlines the steps taken to ensure the conservatism of these LPFs and to extract lessons learned from a large number of calculations.

These methodologies can be applied to safety analyses for other DOE facilities. The ideas presented in this paper should be useful for other analysts doing LPF calculations using MELCOR.

Part 1 Ensuring Conservatism

Introduction

To better understand what a conservative calculation entails, it may be helpful to contrast *conservative* and *best estimate* calculations. Both types of calculations have been used in the nuclear regulatory process. Conservative calculations are performed using assumptions that produce a conservative result *for each step in a process*. Best estimate calculations with associated uncertainty limits are allowed under Nuclear Regulatory Commission licensing rules for some situations (e.g., the emergency core cooling system assessments required for nuclear power plants under 10 CFR 50, App. K).[1] Calculation of uncertainty limits requires relevant, high-quality data and a considerable investment in personnel time. The calculations discussed herein are conservative calculations. This paper goes through each step to show how conservatism can be demonstrated. When doing a conservative calculation, it is difficult to estimate the uncertainties involved as will be seen, though it is relatively easy to ensure that a calculation is bounding.

When evaluating the conservatism of a code calculation, it is necessary to understand the physical phenomena involved. In many cases the best way to examine underlying phenomena is to use another code that was specifically created to predict the phenomena in question. In this paper we use results from the NIST fire codes for comparisons to MELCOR results. Results from the NIST fire codes—Consolidated Fire and Smoke Transport (CFAST)[2] and Fire Dynamic Simulator (FDS)[3]—have been used for comparisons in this work. The CFAST code is a two-zone fire model used to calculate the evolving distribution of smoke, fire gases, and temperature in a small number of compartments in a building. The FDS code is a computational fluid dynamics (CFD) code specifically created to model fire-related phenomena. Both codes are widely used in the fire protection community.

This paper focuses on the phenomenological aspects of ensuring conservatism in MELCOR-calculated LPFs. Obviously, it is also important to make sure that the model is an accurate representation of the facility.

The Base-Case Scenario

The facility scenario that has been the subject of most of the MELCOR LPF analyses is a laboratory fire. Much work on the development of controls has been done using this scenario. It is assumed that transient combustibles (probably waste containers) ignite. These burning transient combustibles ignite polymethyl methacrylate (PMMA) shielding that covers some gloveboxes. This shielding comprises the largest quantity of fixed combustibles in the facility. The material-at-risk (MAR) is finely ball-milled plutonium oxide powder in a glovebox. The gloves burn early in the scenario, allowing PuO_2, which is assumed aerosolized by the fire, into the laboratory room.

The fire curve (the higher curve in Fig. 1) was developed from data taken from a test burn in a fire-testing laboratory on a mockup of a shield module. The test curve was input to CFAST as a base curve, and the procedures in the *CFAST Toolbox*[4] document were used to adjust this curve. Underlying assumptions include that the door between the laboratory and the adjacent corridor, and doors to adjacent laboratories were all open, maximizing the energy release of the fire. Also

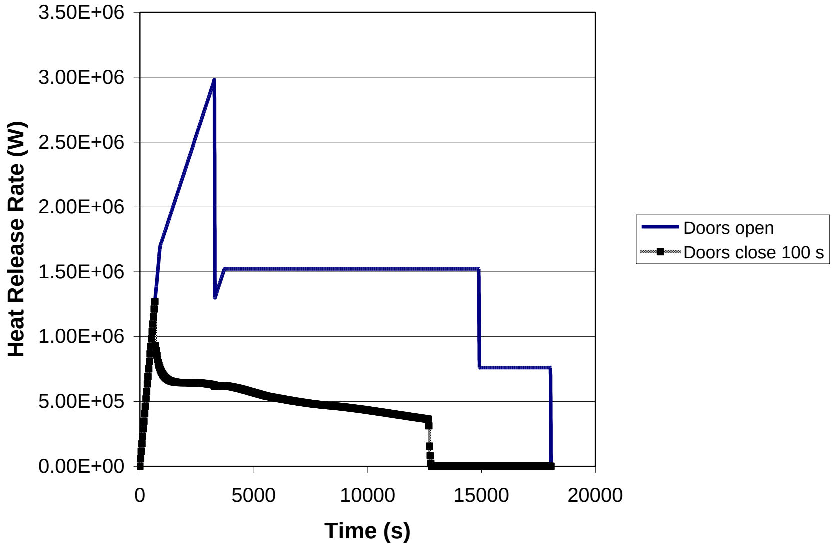

Fig. 1. Heat release rates for PMMA fire in laboratory room with doors open and doors closing at 100 s

shown in the figure is a curve from the same CFAST model but with the doors closed. The curve for the doors open case was used as the driving curve for the MELCOR LPF analyses.

Release of Aerosolized Source Term Material to Fire Room

The release of the aerosolized source term material to the fire room is input to the MELCOR model as a boundary condition. The airborne release fraction (ARF) and respirable fraction (RF) are generally obtained from DOE-HDBK-3010.[5] These quantities along with the MAR give the quantity released. To understand whether or not the aerosolized material input in the MELCOR model as a boundary condition is conservative, several issues related to the release must be examined. These are summarized below.

1. The characteristics of the aerosolized material released to the room or glovebox in the simulation must be conservative. In this study, 1 g of a 1-µm monodisperse aerosol was used as the released material. The 1-g quantity is small enough that agglomeration with a consequent increase in deposition is minimal. In effect, a small tracer release is used rather than a larger release based on MAR, ARF, and RF. The size was also chosen to minimize deposition, though this size is close to the peak size distribution for the finely ball-milled powder in the scenario.

2. Though not entering into the MELCOR LPF calculation directly, a release based on the ARF from DOE-HDBK-3010 is very conservative for the scenario of interest. The experimental work that forms the basis for the relevant ARF used an experimental arrangement in which the test material was directly exposed to higher air velocities than believed likely for this fire scenario. The experimental material had a very different size distribution (15–44 µm). These particle sizes are significantly larger than the MAR sizes. The likelihood of a given particle being entrained is related to the size of the particle. In general, the smaller the particle, the more likely it is to adhere to surfaces or other particles, thus making it more difficult to entrain into an adjacent air stream. This is because Van der Waal’s forces on small particles tend to be large relative to aerodynamic forces.

3. The MELCOR calculations assume a puff release to the inside of a glovebox. Results of a CFD simulation of the glovebox with a puff release and exterior fire were used to define the release to the MELCOR model. Entrainment of particles in the glovebox is expected to be a strong function of the airflows induced by a fire on the shielding outside the glovebox, so the entrainment of particles should occur over time as the fire ramps up. Because doors closing as a function of time is used in these simulations, using a puff release before the doors close is conservative. In the more realistic situation with material entrained over a period of time, material that is entrained after doors close is much less likely to be transported out of the facility.

Transport of Aerosolized Material from the Fire Room to the Adjacent Corridor

Once the aerosolized source term material is released to the room because of the fire, the next step is to ensure that the quantity released from the door between the fire room and the corridor is conservative. To do this requires an understanding of the phenomena in the fire room.

The basics of fire room phenomena are well known. The NIST has conducted an extensive experimental program of fire research. The results from this program have been incorporated into fire codes, two of which (CFAST and FDS) have been used here. Both codes have extensive verification and validation against results of the NIST experimental program.

During a room fire, smoke, combustion gases, and heated air rise to the ceiling. As the fire continues, a hot layer builds downward from the ceiling. Once the hot layer builds down to the tops of doors, a bi-directional flow through an open door can develop. Cold air is drawn in through the bottom of the door and hot air and combustion gases flow out the top of the door. Figure 2 shows the layer height from the CFAST calculation with open doors.

To ensure conservatism in the MELCOR modeling, it is necessary for the model to predict a greater outflow of radioactive aerosol than expected based solely on fire behavior. The aerosolized radioactive material is small and has a small gravitational settling velocity (roughly 1 m/hr). Since we expect this material to be released as a consequence of being in the immediate vicinity of the fire, this material should be carried upward into the hot layer where it behaves in a manner similar to the soot particles generated by the fire. Flow of the aerosolized radioactive material from the fire room to an adjacent corridor occurs primarily with the outflow from the hot layer. Thus, the key to ensuring conservatism for this condition (a room fire with a door open to an adjacent corridor) is to ensure that flows predicted by Melcor from the region with the aerosols exceed the flows from the hot layer as predicted by a fire code.

To create a model to capture the key phenomena discussed above, the fire room was divided into two control volumes separated by a horizontal plane. This division between control volumes was set at a height slightly below the top of the door between the fire room and the corridor. Each control volume was connected to the adjacent corridor control volume by a flow path. As can be seen in Fig. 2, the hot layer grows rapidly until it reaches the top of the door. Once outflows begin from the hot layer to the corridor, the height of the interface between the layers stabilizes briefly before building downward at a much slower rate. Since MELCOR does not have the ability to model control volumes with an adjustable interface, placing the interface between the two control volumes at the height where the CFAST model briefly stabilizes at about the height of the top of the open door is logical.

The aerosol input to the MELCOR model as a boundary condition is released to the upper control volume, representing the transport of aerosol into the hot layer. In most cases the fire energy, which is input as a boundary condition to MELCOR, was partitioned between the layers.

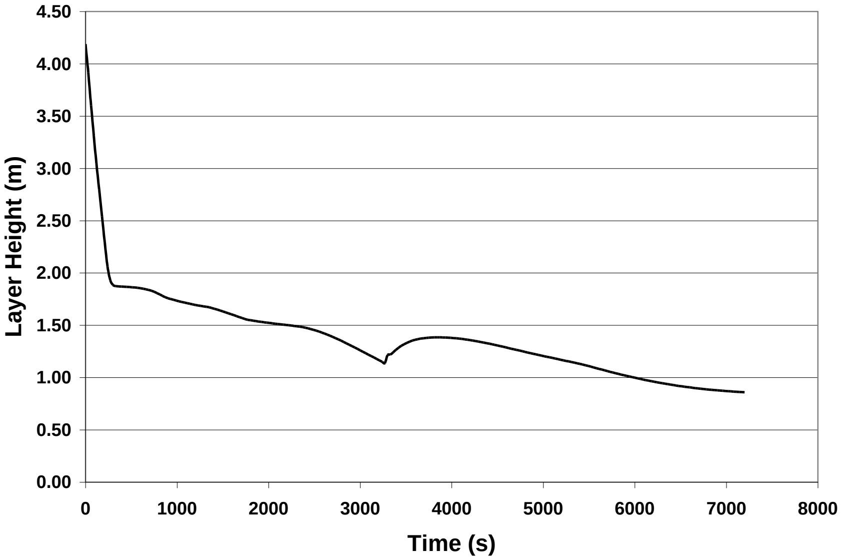

Fig. 2. Elevation of the bottom of the hot layer as predicted by CFAST for a room fire

MELCOR tends to overpredict the fire room temperatures. Partitioning the energy input makes the room temperatures more reasonable when comparing to CFAST results. The key parameter that must be conservatively predicted by MELCOR is the outflow from the hot layer where the aerosolized source term material is located. Figure 3 shows the comparison between CFAST predictions for door outflow and the values calculated by MELCOR. The MELCOR model starts in a condition (hot layer developed to top of door height) that takes about 3 min to develop in the CFAST model. Through the first 20 min of the fire, the MELCOR outflows are significantly greater than the CFAST-predicted outflows. Fire room door closing times between 1 min and 5 min after the initiation of the fire are of primary interest. Some cases have also been evaluated with the door always open. It is clear that the MELCOR calculations are conservative for the release of aerosolized material for the cases with the door closing in less than 5 min. When the door is open longer than 20 min, the door flows are no longer conservative; however, most of the aerosolized material is flushed from the room in well under 20 min. Thus, we expect that the transport of aerosolized source term material from the fire room to the corridor will be significantly greater in the MELCOR calculation than would be expected based on knowledge of room fire phenomena as incorporated into the CFAST code.

A related topic is the release of material from the fire room with active ventilation. The peak door flow from the CFAST calculation gives about 18 air changes per hour from the bi-directional door flow at the peak fire intensity. This compares to 7 to 10 air changes per hour for active ventilation. Thus we expect that active ventilation can reduce the quantity of aerosols released from a fire room to an adjacent corridor through an open door, though not eliminate this release.

A large enough room fire with an open door acts like a pump, drawing cold air in through the bottom of an open door and expelling hot air, combustion products, and smoke through the upper part of the door. When the door is open, flow can be multidimensional and the MELCOR model can be configured to conservatively predict the key flow. A key difference in phenomena occurs when the door between the fire room and the corridor is closed. The fire will be oxygen-constrained and therefore smaller (lower curve of Fig. 1). The hot layer grows to near floor level fairly quickly, and the circulations caused by fire energy acts to mix the atmosphere in the room. Flow in and out of the room is through door gaps and ventilation ducts as the fire pressurizes the

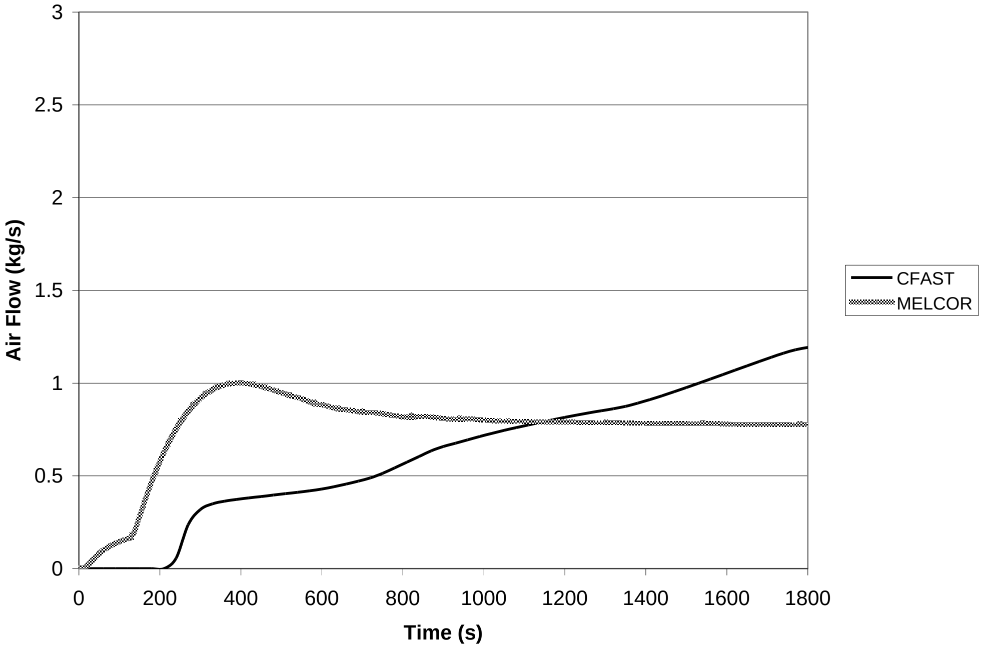

Fig. 3. Comparison between hot layer outflows from MELCOR and CFAST (door between fire room and corridor always open).

room slightly. This pressurization comes from volumetric expansion as the gases in the room heat up and from combustion gas generation. Flows out of the room are expected to be nearly one-dimensional, and therefore within the realm that MELCOR can reasonably predict.

The MELCOR modeling performed for the LANL Plutonium Facility uses as a boundary condition the worst-case fire energy curves developed from a series of CFAST runs. The fire energy used in the MELCOR calculations is not adjusted downward to account for oxygen constraints when doors are closed. Thus, we have excess fire energy; this tends to produce unrealistically high room temperatures, causing more thermal expansion of air and consequently greater flows from the fire room than would be expected (compare curves in Fig. 1). As a result, we get a greater transport of the source term aerosols from the fire room to the corridor when doors are closed than would occur if we used a fire curve that accounted for oxygen constraints. This gives a conservative release value from the fire room when doors are closed.

Combustion gas additions were not included for most MELCOR runs. To produce conservative results, the flows from the fire room containing the aerosolized source term material should exceed the flows identified by the standard tools used for fire modeling. The two control volume MELCOR representation of a fire room does not do a particularly good job of predicting temperatures and flows within the fire room, but it does overpredict the key phenomena, outflow from the room. For the cases with the door open, the pumping action of the fire causes large volumetric flow rates that overwhelm any effects of combustion gas generation. For cases with the fire room door closed, the volumetric expansion from too large a heat addition because oxygen constraints are not considered, exceeds the volumetric combustion gas generation.

Release from the corridor to the environment

The previous sections have discussed the release of the aerosolized source term material to the fire room and from the fire room to the adjacent corridor. This section discusses the release from the corridor to the environment. There are two key questions to address in determining whether or not the release from the corridor is conservative:

1. Do the flows through the corridor exceed the flows that would, in reality, be expected?
2. Could multidimensional effects increase the flow of aerosol-rich hot-air and combustion products from the corridor?

Wind-driven flows through a main corridor are expected to be well-modeled as one-dimensional flows. Getting conservative (larger than best estimate) flows requires conservative boundary conditions driving the flow, conservative flow resistances, and conservative flow areas. The wind-generated pressure fields around the facility were obtained from CFD calculations for eight wind directions and six wind speeds. These calculations included only Performance Category 3 structures around the facility and not the other buildings at the site. These buildings have a significant shielding effect. Thus, the CFD-derived boundary conditions produce pressure differences across the facility that exceed the pressure differences for the actual facility with surrounding structures.

Flow resistances consist of form losses (typically denoted as K) and frictional losses. Form losses occur for contractions, expansions, *tees*, and bends. Frictional losses are a function of the length, flow areas, hydraulic diameter, and roughness. The facility has emergency exits at both ends of the main corridor of interest. One exit consists of an airlock plus a security door. The other exit consists of the door that forms the facility pressure boundary and a security door. In the MELCOR model, we consider only the innermost door that is part of the facility pressure boundary. When doors are modeled as open, the flow areas used are the areas for the innermost doors; the boundary pressures are applied at the location of these doors. To model the door leakage when doors are closed, the door bypass areas were adjusted to get approximately 500 cubic feet per minute (cfm). This is twice the Technical Safety Requirement-identified door bypass flow of 250 cfm at the nominal pressure difference. The door leakage values are measured annually, and the most recent set of measurements were 90 cfm and 130 cfm. The form losses used in door leakage come from a sudden contraction followed by a sudden expansion. The formulas for these are readily available in textbooks and handbooks. In both cases the ratio of the area either upstream or downstream of the door and the area of the contraction enter into the formula. Where the area of the contraction is small compared to the upstream and downstream flow areas, these resistances (K values) reduce to 0.5 and 1. This holds as long as the flow area ratio is small, as is the case when adjusting leakage areas. Then for a given pressure difference across the door, the flow area is the only variable affecting volumetric flow rate.

To summarize, door flows with doors both open and closed are conservative. There are two or three doors in series, and we only consider one of these. This gives a conservative flow resistance (lower than best estimate). When doors are closed, the bypass or leakage flow areas are larger than best estimate values. These factors make the flow resistances at the doors conservative.

The flow resistance through the corridor is determined by the length, flow area, hydraulic diameter, and friction factor. The first three quantities are determined by the geometry, which was taken from facility drawings. The friction factor could be based on either of two possible roughness scales. The first is the roughness of the walls, and the second is the effective scale of door jams, lights, and other objects that are either recessed or protruding from the walls of the corridor. The modeling uses the smaller roughness, though tests showed that there was little effect produced by using the larger roughness scale. The roughness used is 2 mm.

The section above shows why we believe that the bulk flows through the corridor are conservative, i.e., there is more flow than would be predicted by best estimate calculations. The second part of ensuring conservatism is to evaluate whether or not multidimensional effects can contribute to the release of the source term aerosols in a way not accounted for by bulk airflows. Counter-current or bi-directional flow through a hallway from an open door to the outside to a room with a fire is a known phenomenon in relation to fires. Particularly when bulk flow through the corridor is small, the possibility exists for the fire to draw cool air in along the floor toward the fire, assuming the door between the fire room and corridor is open, while hot air, combustion products, and smoke flow along the ceiling toward the open door from the facility to the outside. To evaluate whether or not this is likely to occur for the scenario presented in this paper, FDS models were created and run. Aerosols released from the room should act like the smoke particles modeled by FDS; i.e., they will tend to ride the air currents, with a settling velocity of about 1 m/hr. Tracer particles were also being released on the floor at the end of the corridor next to the open exterior doors. The FDS results show that flow in the corridor is basically one-dimensional for the time period and conditions modeled.

Another simulation was produced using the same model, except that the fire-energy input was taken as a constant 1.5 megawatt, which is about the heat release rate from the fire curve after about 3,500 sec (about 1 hr). This time, there is countercurrent flow in the corridor. The smoke particles released by the fire move toward the corridor exterior door; the particles released from the floor near the exit are moving back toward the fire. The conclusion of this exercise is that the MELCOR model is adequate for the conditions used, but it might not be adequate for a bigger fire or for a case with more time for countercurrent flow to develop.

Part 2 Statistical Analysis of MELCOR Calculations for PF-4

Descriptive Statistics

The set of 127 facility accident cases that were investigated in this study includes a wide range of door configurations, ventilation states, source locations, and modeling strategies. As a general description, there are eight broad categories of input conditions and a total of 164 possible parameter states. For this analysis, all parameter states were considered to be independent categorical random variables that were assigned a value of 0 when not incorporated in the calculation and a value of 1 when the condition was included in the calculation. A complete matrix of wind-dependent LPFs was computed for each accident scenario. Each matrix describes the variation in LPF for all combinations of six wind speeds and eight wind directions. In all, this allowed for more than 6,000 calculations.

Regression Analysis

Sixty-four independent configuration parameters were investigated in the PF-4 LPF study. For a given calculation, only six to eight of these parameters were invoked as needed to incorporate the eight primary parameter categories of (A) evacuation/exterior-door condition, (B) postulated extra door in central corridor condition, (C) fire-room door condition, (D) ventilation-model nodalization, (W) wind boundary condition model, (R) glovebox-fire initiation time, (S) source location and spill/fire, and (F) numerical approximation of fire room. Thus, the design matrix that defines the combinations of parameters that were invoked for all the case studies is relatively sparse.

Multiple linear regression attempts were made to fit a multidimensional straight line to the data using a model of the form $y = X\beta + \varepsilon$ where y are the actual observations, X is the regression matrix discussed above, β is the desired vector of fitted coefficients, and ε is the vector of residual errors. Stepwise regression systematically adds or removes columns from the regression matrix and tests by various performance metrics the degree of fit achieved by using different combinations of parameters. Often, the most desirable fit is selected as the model providing the highest degree of fit using the fewest parameters. This logic acknowledges the fact that a high-order polynomial may achieve a perfect fit to the data even though there is no physical rationale for including all the possible terms. The final set of parameters that are recommended for the *best* model will depend on the criteria used for the search, the starting point for the search, and the systematic method used to sort the combinatorial sets of possible parameter groups. The regression model was run for a value defined as LPF_{eff} that accounts for the variations in wind speed and direction and for its reciprocal $1/LPF_{eff.}$ This combination allowed for investigation into what parameters influenced both high LPF and low LPF.

Results for Linear Correlation of LPF_{eff}

The full linear model achieves a correlation coefficient of 0.76. The reduced model includes only the parameters A2, C1, D1, D2, W2, and S3 with their corresponding coefficients (0.19, 0.11, 0.37, 0.42, -0.16, 0.16) and yields a correlation coefficient of $R^2 = 0.77$. There are clearly some outliers in the data set that are not described well by either of the presumed models, and the degree of fit is likely to be dominated by good agreement with a few of the high-LPF cases, even though the majority of cases examined have low LPF. A discussion of the parameters and their correlation coefficients is presented below.

A2 (Both exterior doors open for 10 min) – Positively correlated variable that has only four cases. However, much like A1 (doors always open), it correlates to high LPFs and distinguishes itself because release timing is such that past 10 min, the release has mostly exited the facility. This high correlation shows the importance of external doors. This parameter plays a key role physically in that without the exterior doors open, a wind field in the main corridor will not be present to remove material.

C1 (Fire room door always open) – Positively correlated variable representing about half the cases run. The correlation to high LPFs is not surprising. The physical reasoning for this parameter playing a key role is that hazardous releases move through the open fire door to the corridor where they are swept out of the building.

D1 and D2 (presence of HVAC ductwork, no HVAC), W2 (use of CFD values for pressure differential across building), and S3 (basement fire) are correlated as the result of sparse data and are a function of the statistical model.

Conclusions that can be drawn are that A2 (doors open for 10 min) and C1 (fire room doors always open) are the two variables that can be concluded to strongly influence high LPFs. These are the conditions that produce the high release conditions because they allow for a direct release of material from the fire to the corridor where high wind conditions allow a *wind tunnel* effect to move material directly to the environment. It is worth noting that the presence of HVAC in the state of *actively on* does not mitigate the high LPF condition.

Results for Linear Correlation of $1/LPF_{eff}$

The full linear model achieves a correlation coefficient of 0.76. The reduced model derived by the stepwise regression algorithm includes parameters (A4, B1, C1, D3, D5, W2, S3, S4, S15) with corresponding coefficients (1.38, 0.39 -1.04, -1.57, 2.00, 1.19, -1.66, -1.79, 1.83), and it achieves a correlation coefficient of $R^2 = 0.65$. The discussion of each parameter and its correlation coefficients is discussed below.

A4 (Exterior doors always closed) – Positively correlated variable representing seven cases. This case is the opposite of A1 (and to a lesser extent A2) and is not a surprising result for a physical condition that produces low LPFs. The exterior doors closed will prevent the presence of a strong wind tunnel effect in the corridor.

B1 (No new corridor doors added) – Positively correlated variable representing about half the cases run. This is a hard parameter to understand physically for a low LPF. It appears in most of the high as well as the low LPF values. In retrospect, it may be that adding a new corridor door (the opposite of B1) does not help reduce LPF significantly for most cases (i.e., a new corridor door does not by itself significantly reduce the wind tunnel effect.)

C1 (Fire door always open) – Negatively correlated variable representing about half the cases run. This result demonstrates the importance of keeping the door closed (or at least not always open), but it also shows that the door alone is not a key parameter. It must be used in conjunction with other parameters to achieve a low LPF.

D3 (HVAC off) – A highly correlated negative coefficient for having fans off and represents about 80% of cases run. Note that the opposite of D3 (parameter D4; HVAC on) was not a high positively correlated variable. The reasoning is that in many cases with doors open and D4 (HVAC on), the HVAC was overcome by the force of the fire and the wind field that was created by having external doors open.

D5 (Bleedoff fan is on), W2 (use of CFD values for pressure differential across the building), S3, S4 (basement fire), and S15 (a spill instead of a fire) are correlated as a result of sparse data and are a function of the statistical model.

It can be concluded that closing the exterior doors and the fire room door has the largest impact on a low LPF. In addition, the closing of the doors will allow HVAC to properly do its safety function of maintaining negative pressure and directing aerosols to the filters.

Conclusions and Insights

The power of parametric studies and statistical analysis is that it can help shed an unbiased light on what a computer model and its results are telling you. In the best case, this type of analysis can even point out interesting results that at first did not occur to the analyst; at its worst it may only confirm the basic understanding of the problem the analyst already had.

For this study several things became clear.

1. The external doors on the east and west ends of the building and their state of closure is very important to having a very high or very low LPF. This is not surprising given that having both doors open enables a wind tunnel effect in the building. In addition, the orientation of the wind is also very important in that the wind tunnel effect is greatly enhanced if the wind is parallel to the main east-west corridor.
2. The fire door that leads from the fire room to the corridor is important. Large LPFs were the result of this door being open; small LPFs were enhanced (although not completed mitigated) by the closure of this door.
3. The HVAC is only helpful if the natural building boundaries such as the external doors and the fire doors are in place. Either the presence of a wind tunnel effect in the corridor caused by the external doors being open or the presence of the fire room pressure overcoming the negative pressure of the HVAC was enough that the intended safety function of the HVAC was defeated.

4. The other important insight is that many parameters such as extra corridor doors, various fire room nodalizations, and changes in release timing seem to have less of an impact on the results. They do impact the LPF but not to the degree other parameters do.

The lesson learned from this study is that the confinement of material is dependent on the system as a whole. The external and internal boundaries such as doors are important, not only in that they help retain material, but also in that they maintain barriers necessary for the proper functioning of the HVAC.

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